Volume 52 January-February 1957 Number 1

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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PUBLISHED SEMI-QUARTERLY

Six Dollars Fifty Cents a Year, One Dollar Twenty-five Cents a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

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Indexed in the Industrial Art Series.

LANCASTER PRESS, INC., LANCASTER, PA.

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AND THE

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ECONOMIC GEOLOGY

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VOL. 52 JANUARY–FEBRUARY, 1957 NO. 1

MINERALOGICAL EVIDENCE ON THE TEMPERATURE OF FORMATION OF THE COLORADO PLATEAU URANIUM DEPOSITS[1]

ROBERT G. COLEMAN

DIRECT evidence of the temperature of formation of the uranium deposits is generally lacking and any estimate or determination of temperature must be based on indirect methods. Certain minerals can be used to establish ranges of temperature based on such properties as melting points, temperature of formation, dissociation and decomposition, temperature of transformation, solid solution-exsolution, and other related properties.

The unoxidized uranium deposits on the Colorado Plateau are considered to represent primary ore that has formed under equilibrium conditions, therefore minerals deposited by the primary ore fluids should exhibit physical and chemical properties conditioned by existing temperatures, pressures, and compositions of these fluids during deposition. Uraninite, coffinite, low-valent vanadium oxides, and sulfides are the most abundant minerals deposited by the ore-forming fluids. Because little is known of the pressure-temperature stability ranges of the uranium or vanadium minerals, these can not, at the present time, be used as temperature indicators. The associated sulfides, however, offer a fertile field in establishing the relative temperatures of formation.

It is known that ZnS has the ability to dissolve appreciable amounts of FeS. In nature pure colorless sphalerite (ZnS) is extremely rare. Most sphalerites contain iron and traces of other elements and are not colorless, but yellowish to brown, some are almost black depending upon the amount of iron substituting for zinc in the structure. Provided sufficient iron sulfide, established by the presence of pyrrhotite (FeS) or pyrite and/or marcasite (FeS_2), was present during the formation of the mix-crystals, the sphalerite would contain an amount of iron determined by the temperatures and pressures existing during the formation of the (Fe, Zn)S mix-crystals.

[1] Publication authorized by the Director, U. S. Geological Survey.

Kullerud (5) has determined the equilibrium diagram of the FeS-ZnS system and has shown that fairly accurate determinations of the temperature of formation (±10° C between 138°–400° C when corrected for pressure) can be made on naturally occurring sphalerites when it is known from polished section study that excess iron sulfide (either as pyrrhotite or pyrite-marcasite) was present when the sphalerite was formed.

Sphalerite forming under these conditions is uncommon in the Colorado Plateau uranium deposits, however two important uranium deposits in Triassic sedimentary rocks contain sphalerite that has formed in the presence of excess iron sulfide (pyrite)—the Happy Jack mine, White Canyon district, San Juan County, Utah and the Hidden Splendor mine, San Rafael district, Emery County, Utah. In both deposits yellow crystals of sphalerite have formed contemporaneously with pyrite and uraninite, therefore application of Kullerud's method on these sphalerites should give the approximate temperature of formation for sphalerite. The sphalerites from each of these localities were carefully purified and quantitatively analyzed for Fe in order to determine the amount of FeS present. Unit-cell determinations were also made as a check on the chemistry since the expansion of the unit cell is a function of the amount of Fe in the mix-crystals when Cd and Mn are absent. The analytical results are listed along with the inferred temperatures.

Location	Unit cell	Wt. % FeS	Temperature
Happy Jack mine	5.4107±0.0003[1]	0.11[2]	<138° C
Hidden Splendor mine	5.4101±0.0002	0.28	<138° C

[1] Determined by G. Ashby, U. S. Geological Survey.
[2] Analyzed by B. Meyrowitz, U. S. Geological Survey.

The equilibrium diagram for the Fe-ZnS system is incomplete below 138° C and a precise temperature cannot be established. However, by projecting the curve downward a range between 55° and 115° C is a rough approximation of the temperature of formation corrected for pressure.

Following Garrels and Richter (1) a reconstruction of the conditions during ore deposition can be given. Stieff and Stern (8) have shown that these ores were deposited in Late Cretaceous or early Tertiary time. The ore-bearing Triassic and Jurassic beds at the end of the Cretaceous were buried under about 10,000 feet of sediment. Assuming a "normal" geothermal gradient (1° C/100 feet) and a lithostatic pressure (using average rock density of 2.7), the temperature would have been about 110° C and the pressure near 800 atmospheres. This temperature is within the same range as that determined by the Kullerud (5) method. Therefore, it would seem that the temperature during the period of ore deposition was not vastly different from the "normal" temperature of the enclosing host rock.

Uraninite has been precipitated from acid solution at temperatures above 50° C by Gruner (2) and Miller (6), and synthetic coffinite has been made by Hoekstra and Fuchs (4) under alkaline conditions at 250° C. Therefore it

would seem that the primary uranium minerals are stable and could form at the temperatures inferred; assuming proper Eh-pH conditions at the time of formation. Other independent observations regarding temperature of formation that have been made are summarized (Table 1). These temperatures are based on methods that are somewhat controversial and further experimental work is necessary to verify their validity. Additional sphalerite determinations by the Kullerud method and measurement by liquid-inclusion methods should be carried out as the present determinations are too few to establish firmly local and regional conclusions regarding all of the Colorado Plateau uranium deposits. It is suggested that the field geologists carefully inspect these deposits in order to obtain suitable unoxidized ore specimens

TABLE 1

TEMPERATURES OF FORMATION INFERRED BY OTHER INDIRECT METHODS ON VARIOUS MINERALS FROM COLORADO PLATEAU URANIUM DEPOSITS

Location	Mineral	Method	Temperature	Source
Cougar mine, San Miguel County, Colorado	High chalcocite and low chalcocite	Inversion (doubtful method)	91° C	Coleman
Cougar mine, San Miguel County, Colorado	Chalcocite-covellite	Exsolution (doubtful method)	75° C	Coleman
Happy Jack mine, San Juan County, Utah				
Cashin Copper mine, Wayne County, Utah				
Happy Jack mine, San Juan County, Utah	Bornite-chalcopyrite	Exsolution (doubtful method)	475° C	Miller (7)
Happy Jack mine, San Juan County, Utah	Uraninite	O^{16}/O^{18} isotope variation (doubtful method too many variables)	Low?	Hoekstra and Katz (4)
Shinarump No. 1 mine, Grand County, Utah				

containing sphalerite or other minerals which could be used as temperature indicators.

This work is part of a program being conducted by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

U. S. GEOLOGICAL SURVEY,
WASHINGTON 25, D.C.,
Aug. 15, 1956

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HEAT AND TEMPERATURE IN ORE DEPOSITION

C. J. SULLIVAN

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ABSTRACT

This paper suggests that temperature zoning and paragenesis reflect the thermal stability ranges of minerals in the solid state, not their relative solubilities in aqueous solutions. The various components of the sulphide facies obey laws similar to those governing the metamorphic facies. Favorable beds and favorable structures depend on susceptibility to thermal activation for replacement, not on porosity or permeability.

Reaction and movement of elements in the earth's crust are responses, principally, to heat, temperature, pressure and chemical gradients. Ore formation is an aspect of these reactions and movements.

INTRODUCTION

If the problems of mineral paragenesis and mineral zoning in ore deposits could be solved, a great stride would be made towards an understanding of the process of ore deposition. The field evidence has suggested to most observers that these phenomena depended to a marked extent on heat and temperature; this evidence was a major basis for Lindgren's (13) thermal classification of ore deposits. However, it has always been difficult to reconcile the undoubted temperature zoning with the idea of solutions. For example, under the vastly varied conditions of nature, the hypothetical solutions must be expected to have a correspondingly varied pH, which must affect the solubility of various metals in various ways; yet under all conditions, mineral zoning and mineral paragenesis are quite constant with respect to temperature. Then, there is no evidence that a cool aqueous solution will carry lead vast distances, while copper requires a warmer solution. Garrels (6) has shown that the effects produced in primary ore deposition are quite dissimilar from those due to the action of known waters (i.e., the waters in the zone of weathering). Lindgren himself recognized these difficulties and characterized the zonal theory as then understood as "a rather weak structure."

Again, the paragenetic sequence for contact-metamorphic deposits is much the same as that found in other primary ore deposits, thus pointing to a common origin. In the contact deposits the thermal zoning of the sulphide minerals is similar in type to the thermal zoning of the non-metallic metamorphic minerals.

This paper represents an attempt to throw further light on these matters, and is an amplification of a previous paper to which the interested reader is referred (21).

In attempting to find explanations for field facts, the writer has found it necessary to refer to modern texts on physical chemistry, and that by Glasstone (8) has been utilized extensively in this case.

THERMAL STABILITY

As stated by Turner and Verhoogen (22), if a system originally in equilibrium is disturbed by a rise in temperature, the pressure being constant, reaction will proceed in such a direction as to be endothermic, and will tend to result in a fall in temperature. Because the reaction is endothermic, as temperature rises, the minerals with low heats of formation become unstable and are replaced by minerals with higher heats of formation.

Heat of Formation and Mineral Association

This points to the importance of heats of formation as an index of mineral associations. In Figure 1, the heats of formation of some well-known oxides are arranged in ascending order. The sulphides fall below the oxides in this list.

It will be seen that this arrangement is reminiscent of a temperature sequence in nature. Those oxides with the higher heats of formation are found in basic igneous rocks which are formed at high temperature. The

descending sequence passes through the granitic and pegmatitic phases, thence to oxide ores. It is important to note that there is no break between the ore-forming and rock-forming processes, such as could be expected if the ores were taken into solution at the end of the pegmatite phase. The observed sequence simply reflects temperature stability ranges. Further, it is sig-

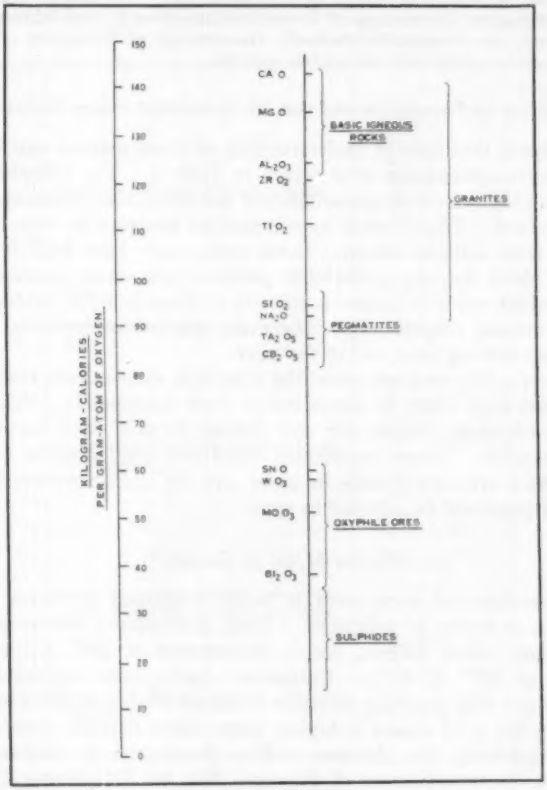

FIG. 1 HEAT OF FORMATION OF OXIDES OF CERTAIN OXYPHILE ELEMENTS (DATA FROM RANKAMA AND SAHAMA, 1949.)

nificant that SnO_2, WO_3 and MoO_3, are commonly associated in nature and have very similar heats of formation.

Heat of Formation and Goldschmidt's Classification of Elements

Rankama and Sahama (17) deal with the relationship between the heat of formation of compounds from the standard states of the elements, and the im-

portant classification of the elements by Goldschmidt (9) into lithophile, chalcophile and siderophile types.

> The distribution of electropositive elements among metal, sulphide and silicate phases is controlled by the free energies of formation of the corresponding sulphides and silicates, as compared with those of ferrous sulphide and ferrous silicates . . . and the heat of formation of a compound from the standard states is usually the prime contributor to its free energy of formation. . . . The oxides of the lithophile elements have higher free energy of formation than does that of ferrous iron. On the other hand, the elements with lower free energy of formation of the oxides belong to the siderophile and chalcophile groups.

Heat of Formation and the Electromotive Force Series

It is believed that further understanding of these matters can be obtained from the electromotive force series given in Table 1. The lithophile elements are those with high electrode potentials and low ionization potentials—i.e., they are easily ionized. These metals have a marked tendency to form high energy compounds with suitable anions. These compounds have high free heats of formation. With decreasing electrode potential, one passes successively from the metals, which occur in nature as silicates to those found as oxides, sulphides, and native metals, respectively. There are gradations between all groups, some elements linking from one to the next.

Thus in a cooling rock sequence, the lithophile elements are stabilized early because of the high heats of formation of their compounds. When this occurs, the ore-forming metals are still mobile because their compounds are thermally unstable. Those compounds which are most unstable (thermally), not those which are most soluble in water, are the last to become fixed in the crust. This point will be referred to again.

Native Metal or Sulfide?

The mineralogy of many ores is better explained in terms of thermal stability than in terms of solubility. Thus, gold occurs native or combined with tellurium. Gold sulfide, Au_2S, decomposes at 240° C, while Au_2S_3 decomposes at 197° C, (11). Calaverite, $AuTe_2$, decomposes at 472° C. Gold sulfides are thus generally unstable in nature while gold tellurides survive; in general, native gold occurs in higher temperature deposits than do the gold tellurides. Similarly, the platinum sulfides decompose at comparatively low temperatures, the temperature of decomposition for PtS_2 being 225–250° C, (11). Thus, platinum may occur in nature as a native metal, though it is also found as the sulfide and arsenide.

In accordance with the position of copper in the electromotive force series, copper sulfides are also comparatively unstable at elevated temperatures. Thus, covellite decomposes at 220° C, (11). Native copper is usually associated with basic lavas, which pass through a very high-temperature phase; at these temperatures, the sulfides were probably unstable. Bismuth and silver are in the same category; in each case, the native metal (in the primary zone only) would be the higher temperature form.

Thus, with increasing electrode potential ease of dissociation decreases; thermal stability of compounds increases. These factors, which have a marked relationship to ore deposition, have nothing to do with solubility in water.

TABLE 1*

METALS ARRANGED IN ELECTROMOTIVE FORCE SERIES SHOWING GEOLOGICAL SIGNIFICANCE. REFERENCE IS MADE IN EACH CASE TO OCCURRENCE IN THE PRIMARY (THERMAL) ZONE

Element		Ion	Electrode Potential
Li	Occur as silicates (ionic bonding)	Li+	+2.959
RB		Rb+	2.926
K		K+	2.924
Ca		Ca++	2.87
Na		Na+	2.715
Mg		Mg++	2.40
Al		Al+++	1.70
Be		Be++	1.69
U	Oxide	U++++	1.40
Mn	Partly sulfide (ionic-covalent bonding)	Mn++	1.10
Zn	Occur principally as sulfides (covalent bonding)	Zn++	0.762
Fe		Fe++	0.441
Cd		Cd++	0.401
Co		Co++	0.278
Ni		Ni++	0.231
Sn		Sn++	0.136
Pb		Pb++	0.122
Fe		Fe+++	0.045
Sb		Sb+++	−0.10
Bi	Occur as native metals and as sulfides (metallic-covalent bonding)	Bi+++	−0.226
Cu		Cu++	−0.344
Cu		Cu+	−0.470
Ag		Ag+	−0.797
Hg		Hg++	−0.799
Pd	Occur as native metals (metallic bonding)	Pd++	−0.820
Pt		Pt++++	−0.863
Au		Au+++	−1.360
Au		Au+	−1.50

Increase in Ionic Bonding

* After Hodgman (11).

Metallic Melting Point

As shown in Table 1, the sulfides have generally low heats of formation compared to the oxides and silicates, and, in a broad way, the passage from the sulfide to the oxide and silicate facies represents a temperature zoning. However, in detail, the temperature sequence in ore deposition cannot be related directly to the heats of formation of the sulfides. Some of these are shown in Table 2 below:

TABLE 2*

FREE ENERGY OF FORMATION (− AF°) OF SOME SULFIDES FROM STANDARD STATES OF THE ELEMENTS IN KILOGRAM-CALORIES PER GRAM ATOM OF SULFUR AT ROOM TEMPERATURE

Sulfide	Free energy of formation −AF°
ZnS	40.4
CdS	33.5
MoS_2	27.1
$FeS_{\downarrow}$	23.4
WS_2	23.1
PbS	22.7
Tl_2S	22.5
NiS	21.3
CoS	21.1
Cu_2S	20.6
PtS	18.6
Bi_2S_3	13.0
Sb_2S_3	12.3
Ag_2S	8.7

* After Rankama and Sahama (17).

Apart from the evidence of the Table, the lack of direct relationship between heats of formation of sulphides and temperature sequences in ores is fairly clear in the case of gold and other metals that occur native in nature. The stability temperatures of the compounds are low, but the minimum temperatures at which the metals are deposited in ores are comparatively high. If all metals occurred native in nature, it might be expected that the metallic melting point would bear a relationship to the temperatures at which their lattices could be thermally disturbed—temperatures at which they could be activated for chemical reaction and movement. There is much evidence that these temperatures need not be the melting points themselves as diffusion and other allied phenomena become appreciable at temperatures well below the melting point.

As shown on Table 1, there is a continuous gradation from metallic through covalent to ionic bonding from the bottom to the top of the electromotive force series. Metallic melting point as an index of thermal stability must be expected to be most significant for those metals with dominantly metallic bonding and the correlation should decrease with the increase in ionic bonding.

It is submitted that this is the case. Figure 2 shows the common ore elements which form dominantly metallic or covalent bonds, arranged according to their metallic melting points. The sequence shows a close relationship to the associations found in ore deposits, indicating the dependence of these associations on thermal stability, not on solubility. These associations have been discussed in more detail elsewhere (21).

Volatility

Brown (2) pointed out a very valuable analogy between the volatility of sulfides and their distribution in temperature zones. This led him to postulate that ores are more likely to have travelled as vapors than in watery solutions. In the writer's opinion, this conclusion is correct. Hsiao and

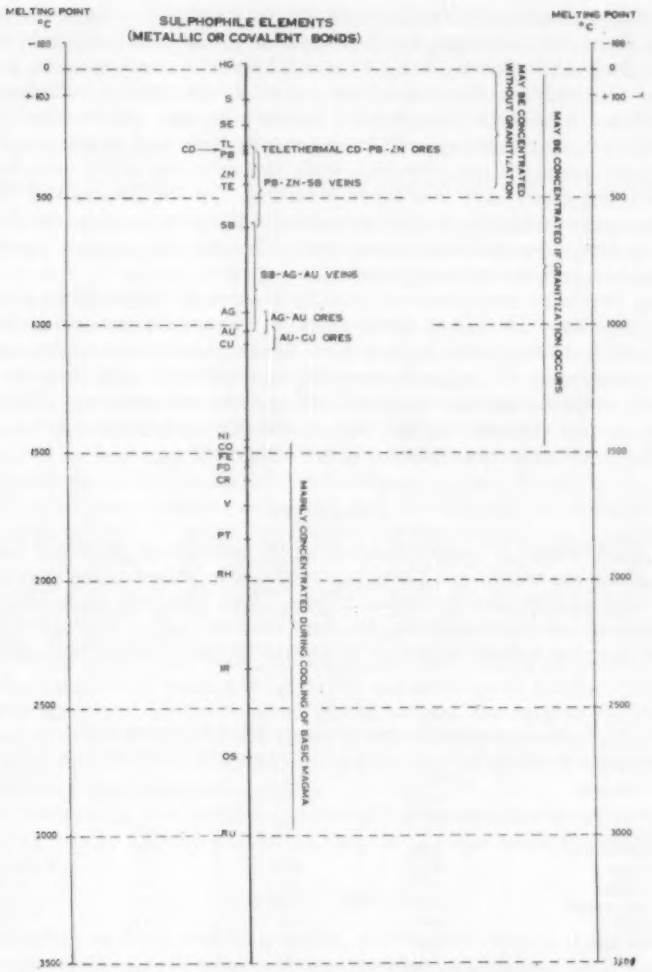

FIG. 2 RELATIONSHIP OF METALLIC MELTING POINT OF SULPHOPHILE ELEMENTS TO TEMPERATURE OF DEPOSITION OF SULPHIDES

Schlechten (12) and Schlechten (19) have presented experimental evidence on the volatility of various metallic sulfides, and the sequences they give correspond well with the paragenetic sequences. The geological significance of these results has been well shown by Edwards (4). Hawley (10) has also shown experimentally that sulfides may move under the influence of heat.

The direct volatilization of the sulfide is not applicable to the movement of

all metals as some sulfides dissociate before volatilization occurs. As suggested above, these are commonly the sulfide of the metals towards the bottom of the E.M.F. Series (Table 1) which have a tendency to occur native in nature. Possibly, in these cases, the metals themselves are volatilized after the sulfides have been dissociated. Fenner (5) has shown also that the chlorides of many common ore-forming metals have high vapor pressures at reasonable geological temperatures, while the chlorides of the ionic bonding, rock-forming bases have low vapor pressures. In the presence of chlorine, the ore metals could thus be distilled off from the rock-forming metals. This point is used in metallurgical processes. Chlorine and chlorine compounds are common in many volcanic gases.

The geological importance of volatility is strongly suggested by a valuable study by White (23) of hot spring deposits. These deposits are of the comparatively low temperature type and are akin to Lindgren's epithermal class. The characteristic ore minerals occurring in commercial quantities are sulfur, mercury, cinnabar and the compounds of arsenic and antimony. These substances are not characterized by their relative solubility in cool water, but by their high volatility at comparatively low temperatures.

Hardness

In 1924 Gilbert (7) noted that the harder minerals are generally deposited early in the ore sequence. There is a relationship between hardness, melting point, heat capacity, and thermal stability. Thus, Glasstone (8, p. 422) states, "elements of low compressibility, i.e., hard elements, and of high melting point should give the highest values of θ, (characteristic temperature) and hence

TABLE 3

CHARACTERISTIC TEMPERATURES OF SOLID ELEMENTS (° C)

Element	From Heat Capacity	From Elasticity	From Compressibility	From Melting Point
Lead	88	73	103	85
Cadmium	150	—	124	133
Silver	215	214	195	210
Copper	315	332	270	330
Aluminium	398	402	314	360
Iron	453	—	310	396
Carbon	1860	—	—	1570

elements with such properties should only attain the classical atomic heat of 6 cal. deg.$^{-1}$ at relatively high temperatures. The elements carbon (diamond), boron and silicon provide excellent confirmation of this deduction. The low atomic weight of these substances is, of course, a contributory factor, as may be seen from the equations mentioned, but it is not the most important; lithium, for example, has a low atomic weight, but its atomic heat capacity attains a value of 6 cal. deg.$^{-1}$ at room temperature because it is a soft metal of low melting point."

Table 3 shows characteristic temperatures of some elements calculated from various properties of the elements, including hardness and melting point.

Characteristic temperature is believed to be most important to an understanding of heat capacities and hence of the thermal stability of metals, because, in the Debye treatment of the heat capacity of solids, it is the only property that is dependent on the nature of the metal itself (8, p. 421). The characteristic temperature θ is defined mathematically as $\frac{hv_m}{k}$, where h is Planck's constant, k is Boltzman's constant, and v_m represents the maximum vibrational frequency of the individual atoms. The vibrational frequency is the only variable and it is through this that characteristic temperature is related to melting point.

In non-mathematical language, the number of calories which an element will absorb per degree rise in temperature is not a constant. The atomic heats of all elements diminish with decreasing temperatures. Those elements with low characteristic temperature acquire their full heat capacities at low temperatures and vice versa. Thermal stabilities of elements and compounds are related to heat capacity (8). For a fuller treatment of thermodynamic background the reader is referred to the standard works. It may be significant that the minimum temperature at which lead, for example, is mobile in nature is the order of 100° C which approximates to the characteristic temperature of lead. In general, the characteristic temperature shows a considerably greater relationship to the minimum temperature at which metals move and are concentrated in nature than do the melting points of the metals. However, the two are related.

Referring again to hardness, the argument refers mainly to metals. However, the hardness of sulfides is related to the hardness of metals. A tabulation will show that, for the common simple sulfides, the ratio of the hardness of a sulfide to the hardness of the metal is commonly of the order of 0.7 to 1.1. The actual ratio is likely to depend on the bonding, as does the significance of melting point discussed above.

Hardness, then, is a broad indication of the temperature at which thermal instability may be attained and, in this way, is a similar index to melting point and volatility.

Chemical Activation

According to the law of mass action, the rate of chemical reaction is proportionate to the active masses of the reacting substances. Only activated particles are capable of taking part in chemical reaction. In geology it is believed that activation for chemical reaction commonly results from increased temperature and, as shown by susceptibility to metamorphism, various types of rocks and minerals may be activated at varying temperatures depending on their bonding energies, entropies and heat capacities at these various temperatures. Each substance has a specific energy of activation and, in general, the larger this energy the higher the temperature at which the reaction rate becomes appreciable.

A full discussion of the theory of chemical activation and reaction rates is

beyond the scope of this paper and the reader is referred to the standard works. The important point for the present discussion is that chemical activation energies relate through their common dependence on critical temperatures with factors such as transition points, melting points, volatility and activation energies for diffusion. These concepts are considered to be of great importance in an understanding of features such as "favorable host rocks," and of the reaction between ore-forming elements and country rock.

The subject of crystal kinetics which treats of the activation energies for diffusion and chemical reaction is discussed from the geological point of view by Ramberg (16).

PRESSURE ACTIVATION

In the above discussion, the effects of pressure have been ignored, though it is well-known that pressure is substantially important in such processes as chemical activation and activation for diffusion. Pressure also affects transition points, melting points and vaporization temperatures. Thus, according to Glasstone (8, p. 464), the transition point between rhombic and monoclinic sulphur should be raised 0.045° per atmospheric increase of external pressure. The change in transition point with increasing pressure is positive, because the specific volume of monoclinic sulfur is greater than that of rhombic sulfur. If a transition leads to a decrease in specific volume, external pressure decreases transition points and other critical temperatures. This could apply in geological processes.

On the other hand, it is to be expected that, as ore-forming materials move into regions of comparatively low pressure, the temperature required to disturb them thermally might suddenly increase and would thus lead to the stabilization of the minerals. This will be further discussed in connection with the localization of ores at positions of tension in zones of structural weakness.

Other effects of stress on mineral stability may be observed in the twinning that is produced in calcite, for example, under conditions of comparatively low load. The twinning indicates a rearrangement of the crystalline structure and is equivalent in some respects to the transitions produced by temperature.

A conclusion of this brief discussion is that pressure as well as temperature plays an important part in the activation of atoms, ions and molecules for chemical reaction and movement. Generally, there is a combination of the two. However, in ore-forming processes especially, heat and temperature are the dominant variables.

FORCES DRIVING REACTION AND MOVEMENT

In the above discussion an attempt has been made to indicate the manner in which the materials of the earth's crust may be prepared for chemical reaction and rearrangement. In the present chapter some ideas will be presented that may help to indicate the forces which may lead to new combinations of materials and also the transfer of materials from one point to another. The concentration of ore deposits is an aspect of these phenomena.

Heat, Temperature and Geochemical Reactions

Repeating a previously quoted statement by Turner and Verhoogen (22), if a system originally in equilibrium is disturbed by a rise in temperature, the pressure being constant, a reaction will proceed in a direction such as to be endothermic, and will tend to result in a fall in temperature. In geological terms, this is equivalent to saying that, as temperature rises, crystalline compounds are formed which are stable at the given temperature. Heat is absorbed and minerals with high heats of formation result. The reaction tends to be self-quenching as it results in a fall in temperature. One of the main driving forces in geochemical reaction is thus heat.

This principle appears to the writer to apply to such processes as granitization and ore-formation.

If, within a group of rocks composed of minerals with low heats of formation, a focus of heat is established, the heat can be absorbed by the migration of the highly electropositive cations (Table 1) to this focus, and the stabilization there of the high bonding-energy, granite-forming minerals. These minerals have high heats of formation and their crystallization absorbs a great deal of heat and thus tends towards the establishment of stability. The formation of granite can thus be viewed as a stabilizing process accompanied by the absorption of heat and the sealing of zones of weakness in the earth's crust. It is suggested that, owing to the same principle, the components of ferromagnesian and other minerals with high heats of formation, under conditions of granitization, tend to migrate towards the deep hot zone which is their natural habitat, to form rocks of the anorthosite and allied type. On the other hand, a basic igneous rock is commonly the last to be transposed during granitization. This is because of the stability of the minerals at comparatively high temperatures.

The relatively electronegative cations, to which belong most of the ore-forming elements, form compounds which have relatively low heats of formation and may stabilize at temperatures much lower than those required for the formation of granite. These elements migrate down the thermal gradient to points at which the temperature is no longer sufficient for the thermal disordering of their sulfide lattices and stability is possible.

An example of what might be called electrochemical directionalism in geology may be observed at most contacts between limestone and granite. Almost invariably, the highly electropositive calcium moves out of the limestone and is replaced by silica, which is almost amphoteric. There is little indication that the lime moves into the cooler regions and yet vast quantities of it disappear. It is suggested that it moves towards the hotter rocks. In a very similar way, the relatively electronegative ore-forming elements, copper, lead, zinc, etc., move into the limestone, the distances they move being a function, in part,[1] of the stability ranges of the sulfides and of temperature distribution in the limestone. They move down the temperature gradient as against the contrary movement of the more electropositive cations.

[1] The presence of activated water, carbon dioxide and/or other compounds will also affect thermodynamic equilibrium.

In metamorphism, increased temperature leads to the development of more stable minerals with higher heats of formation. In many cases, the materials already present are merely rearranged, and the amount of movement is small. In cases of granitization and related metal concentration processes, as discussed above, the establishment of thermal stability involves the movement and rearrangement of vast quantities of material. Thus, it is impossible to deny that very large masses of quartzite, shale, limestone and lava have been converted to granitic paragneiss which indicates the broad truth of the statement immediately above. In many cases these changes have taken place without substantial change of volume or attitude. Quite probably, geological science is not yet in a position adequately to explain these processes. This is no reason not to accept the fact that large-scale migration of material does occur.

Consideration of the above aspect of the problem shows that, ultimately, the driving energy for the chemical reaction and redistribution of elements which takes place in such processes as granitization and ore deposition is heat. If no heat is supplied these processes do not take place. However, the phenomena may also be regarded from the point of view of the differences of electrical potential which may develop in the crust subsequent to the introduction of heat, and these differences of potential may help to explain the transfer of materials. Thus, ionic diffusion is slow under the influence of little or no potential difference but can be speeded up greatly by the imposition of large voltages.

In order to discuss the idea in mind here, it is necessary to examine the concept of critical potentials and ionization potentials (8, p. 50). A critical potential is a measure of the amount of energy required to raise an electron from one energy level in an atom to the next. One of the critical potentials is the ionization potential which is required to transfer an electron from a normal quantum level to infinity, thus producing a positively charged ion. It is the inverse of the electrode potential (Table 1) though the latter is normally measured in different units, i.e., in relation to hydrogen, as having a zero electrode potential.

Atomic spectroscopy shows that the energy of excitation which is required to lift the electrons to their various resonance and ionization potentials may be supplied by heat. Supposing that, as is common in the earth's crust, masses of material have been accumulated (as during sedimentation) which have substantially different average ionization or resonance potentials. If heat is now applied and a certain level of electron excitation is achieved, very large differences of electrical potential may develop. Taking into consideration the very large masses of material involved the potentials may be enormous indeed.

The general principle involved is not essentially different from that of the thermoelectric couple except that the resistance to the flow of current is enormously higher and that, therefore, the discharge of the potential differences built up during heating is much slower than in the case of the artificial thermocouples. The discharge is considered as taking place by the flow of charged particles, and results in a rearrangement of materials depending on their position in the electromotive force series.

Apart from electrochemical theory, it is an observable fact of nature that,

when heat is applied, metals distribute themselves broadly into lithophile, chalcophile and siderophile groups, i.e., in accordance with their position in the electromotive force series.

As indicated above under the discussion of volatility, many ore deposits could be regarded as the products of distillation from heated rock masses of the relatively volatile components, including water.

Perhaps this supplies a more or less adequate picture of what happens in volcanic belts where large bodies of lava are produced. However, volatility does not appear to account, in itself, for the complex reactions which proceed under conditions of metamorphism and granitization, with which processes ore concentration is commonly associated. Volatility appears to be one aspect of a broad thermodynamic problem.

APPLICATION OF PRINCIPLES

Thermal Zoning

Temperature zoning is readily observed in a contact-metamorphic deposit in limestone. Where granite intrudes limestone it is convenient for the purpose of the present discussion to regard the boundary of the granite and skarn as representing approximately a geoisothermal line, while a similar but lower temperature line marks the boundary between skarn and marble. The marble may fade out into ordinary limestone.

The ore minerals as well as the metamorphic minerals show a definite arrangement with respect to these various temperature zones.

The high-temperature oxyphile ores, such as scheelite, occur close to the granite contact; chalcopyrite is confined to the skarn zone; and lead and zinc sulfides may occur on the cool side of the marble line. This arrangement, like the arrangement of the metamorphic minerals themselves, reflects the temperature stability ranges of the various sulphides and has nothing to do with their respective solubilities, or with the relative porosities of the rocks (although the latter explanation is sometimes given for this distribution).

For ore deposits in shear zones, temperature zoning is not nearly so readily discernable. This is thought to be due to the fact that any given temperature zone normally has a great vertical extent compared to depths of mining. However, the paragenetic sequence in the contact-metamorphic deposits is quite similar to that found in other types of deposits and the same principles are thought to apply.

In the study of many types of ore deposits, but especially in those of the contact type, the reconstruction of the former position of geoisothermal lines is commonly found to be of very substantial prospecting significance.

Paragenesis

The paragenetic sequence has been found to apply universally and thus has important significance.

As pointed out previously, the paragenetic sequence of the sulfides is related to the hardness of the sulfides, which, it was suggested, is indicative of the temperatures at which these sulfides remain stable in nature.

Some relationships between paragenesis and temperature were well investigated by Virginia Ross (18). She showed that it is possible to develop sulfide minerals, not formerly present, simply by maintaining elevated temperatures, well below the melting points of the minerals. Her work led her to postulate "the simultaneous and chemically equivalent interchange of two different kinds of metal ions that migrate in opposite directions through the relatively stable sulphur network of a developing intermediate phase."

It is common to observe in mines that post-ore dikes will cause the rearrangement of sulfides and in some cases the formation of sulfides of different composition. A specimen of coarse galena found in the Sullivan Mine, Kimberley, British Columbia, after a recent local fire, was interesting in this respect. One side of the specimen had been converted to red lead, and, on the opposite (cooler) side, small new crystals of lead sulfide grew. This shows that heat itself is capable of affecting the paragenetic sequence. Hawley (10) has presented similar evidence. In many descriptions of ore deposits, the author speaks of several periods of mineralization which he tends to equate to various cycles of magmatic activity, accompanied by corresponding hydrothermal solutions. It is suggested, however, that, as in the case of thermal zoning, the governing principle is the relative stability of the minerals at varying temperatures. Thus, at any time at which a deposit was reheated, reactivation of the ore-forming materials could occur, and the paragenetic sequence could be modified.

Favorable Rock

It is believed that an understanding of "favorable rock" is obtained if it is noted that favorable host rocks are rocks that may readily be metamorphosed. It has commonly been recognized that a rock which is said to be "chemically active" is favorable for ore. But the role of temperature in chemical activation has already been discussed and, it is suggested that a rock that can be chemically activated at comparatively low temperatures, is a rock that is susceptible to replacement by ore, as it is also susceptible to metasomatism and metamorphism.

For the purpose of illustrating this principle, a comparison between sandstones and limestones may be useful. Sandstones are commonly quite porous, but they are relatively poor host rocks for ore deposits; they are also little affected by thermal metamorphism. Thermodynamically, limestone is quite different, especially when impurities are present. At comparatively low temperatures, recrystallization to marble occurs; at more elevated temperatures the formation of amphiboles commences and the whole calc-silicate suite is readily formed. This indicates that a comparatively large percentage of the atoms composing the calcite lattice may be activated for diffusion and for chemical reaction at temperatures at which sandstone is merely recrystallized to quartzite. The laws of chemical reaction imply that the reaction rate between invading activated metallic ions or molecules and a host rock will depend, not only on the number of invading ions and molecules that are activated, but also on the proportion of activated particles in the host rock itself. It is

believed that it is in this sense that limestone is a favorable host rock for ore. There is no evidence that its favorability depends on relative permeability.

A further comparison may be made between shale and sandstone. In very many deposits, sulfides replace shale and slate in preference to sandstone and conglomerate, even though it is clear that the latter rocks are the more permeable. Commonly, the shale and slate have very low porosites and permeabilities indeed.

Again the criteria of metamorphism appear to apply. When sandstone is heated, no great change occurs until the temperature is reached at which it is possible to introduce the alkaline bases and feldspars are formed. On the other hand, shales yield the andalusite-sillimanite sequence of minerals well before the granitization stage—they are comparatively "reactive" rocks. The marls are more susceptible than are ordinary shales, both to metamorphism and to replacement by sulfides.

Some would argue that the favorability of lime-rich rocks derives from their neutralizing effect on acid, ore-bearing solutions. Apart from the fact that many investigators have concluded that these solutions are alkaline, it is difficult to visualize a solution that always remains acid, even after it has passed through vast thicknesses of limestone.

Hydrothermal Alteration

In recent years, a great deal of attention has been paid to hydrothermal alteration which, in some instances, has proved to be useful in exploration (14). The common association of hydrothermal minerals with some ore deposits has, however, been regarded as strong evidence for the validity of the hydrothermal solution theory (15), and the writer considers that this is not necessarily the case.

As has been suggested previously in this paper, it is important to consider the temperature stability ranges of minerals, which commonly throw a good deal of light on their origin. Bronson Stringham (20) has collated evidence which shows that the temperature field for many of the common hydrothermal minerals such as kaolinite, dickite, gibbsite, nontronite, montmorillonite and the zeolites lie in the range 50° to 300° C. It is a fact of observation that marked hydrothermal alteration is associated mostly with granite or with volcanic rocks, indicative of high temperature. In the case of granitic activity or granitization, the feldspars and other granite-forming minerals are probably stable by the time temperature falls to 450–400° C. At these temperatures, neither the hydrothermal minerals mentioned above, nor the sulfide-forming elements, are fixed in stable compounds, and they tend to collect at points where the temperature is still relatively high, although the main part of the mass has cooled. The temperature range of stability for the hydrothermal minerals is, in fact, rather similar to that of the sulfide-forming elements, and it is considered that their association depends to a substantial extent on this fact. Water is a common substance which, along with many ore minerals, is volatile at comparatively low temperatures.

The hydrothermal solution theory requires that hydrothermal alteration

should accompany all primary sulfide deposition, and this is not the case. Thus, for the telethermal lead-zinc deposits, which may be concentrated at temperatures below those at which granitization occurs, hydrothermal alteration is not at all marked. This may be explained as being due to the fact that the temperature never rises to the level at which hydrothermal minerals would be rendered unstable, and they thus remain dispersed rather than being concentrated along with the sulfide phase as in granitization. By contrast, during granitization, hydrothermal minerals distributed in sediments are rendered unstable by the temperatures attained and are again stabilized in a more concentrated form when the temperature falls as described above. Thus hydrothermal alteration is regarded as being something that may accompany ore deposition, but does not necessarily do so. In this respect it is similar to granitization itself (21).

Structure

Worldwide experience has shown that there is commonly a relationship between faults, shears, folds and ore.

Structural control of ore deposition may be approached from four aspects (a) resistance to the movement of activated particles; (b) susceptibility to thermal activation for replacement; (c) increased stability of minerals due to reduction of pressure; and (d) susceptibility to penetration by water and other thermally unstable substances. There are, of course, numerous other aspects.

Electrical Resistance to Movement.—Movement during faulting and shearing destroys strongly bonded crystals, which are replaced by laminated rock. It is difficult for an activated ion to diffuse through a crystal, and experiments show that the diffusion normally takes place along grain boundaries or cracks. Shearing creates many such pathways along which the electrical resistance to diffusion is low.

Susceptibility to Thermal Activation.—As previously suggested, for a rock to be replaced by activated invading particles, that rock itself must be activated in some way. A sheared rock has suffered a large reduction in bonding energy compared with the rock outside the sheared zone, and is thus more susceptible to thermal activation. It is a "favorable rock" in the sense defined above. Under the influence of stress and heat, rocks may become foliated and lineated. This implies that the mineral components have been activated allowing the minerals to grow in the direction of minimum stress. This activated rock is suitable for replacement by ore and it is commonly found that the latter plunges with the lineation. It may be worth noting that sheared zones are susceptible to replacement, not only by sulfides, but also by such granitic rocks as quartz porphyries and albite porphyries. Is this type of replacement also due to solutions?

Effect of Pressure Reduction.—Structural studies commonly show that replacement is most intense at positions of comparative tension. Ramberg (16) shows that an increasing percentage of particles are "evaporized" with increasing pressure. If these evaporized particles reach a shear zone in which pressure is suddenly reduced, stabilization of the minerals is likely to ensue.

The discussion above on the relationship between pressure and temperature of activation is relevant here; in many instances, a fall in pressure should raise the minimum temperature at which a mineral would be rendered unstable.

Susceptibility to Penetration by Water and Other Thermally Unstable Substances.—It is not the intention of the writer to deny that water (or steam) accompanies the deposition of ore in many instances; there is abundant evidence that it does. Openings and pathways in the form of faults, fractures, and brecciated zones, or volcanic vents, provide channels through which mobilized water (mostly steam?) as well as volatilized or otherwise thermally disturbed metals and metallic compounds may readily move. However, this mixture of steam and other volatiles should not be called a solution. Additionally, as pointed out above, the localization of many deposits is probably not due to the presence of openings, but to the presence of rock that is susceptible to replacement at temperatures at which the ore minerals may be stabilized.

Metalliferous Provinces

H. E. McKinstry (15) recently raised many provocative and interesting points concerning the origin of ore deposits. The scope of the present paper does not permit an attempt to discuss all of these, but it seems to the writer that the question of "lateral secretion," raised by McKinstry, is relevant here.

Firstly, it is believed that one of the hindrances to an understanding of ore-genesis has been the attempt, both by early lateral secretionists and by later hydrothermalists, to impose a single, universalist interpretation for all metalliferous provinces and deposits. Most lead-zinc provinces are co-extensive with definite sedimentary rock groups. In many cases, these groups belong to a particular sedimentary facies. The association of lead-zinc with algal reefs is common, also with the near-shore banded iron formations. In the telethermal lead-zinc deposits, concentration occurs below the temperature of granitization and no igneous rocks may be present. Concentration will also be effected, however, if granitization occurs.

Uranium provinces also, are normally co-extensive with definite groups of sedimentary rocks, or with rocks that were formerly sedimentary. Again, algal reefs may be important prospecting guides. However, in the writer's opinion, it would be quite misleading to classify a red-bed uranium province, such as that of the Colorado Plateau, with a province such as the one around Lake Athabasca, Canada, where much of the sedimentary belt has been converted to granitic paragneiss. The metamorphic history has been greatly different in the two cases. It is common in a red-bed sequence to find evidence that copper and uranium have been reconcentrated by meteoric waters. This is lateral secretion in the old sense. The amount of movement is commonly small and ore is clearly associated with a particular sedimentary facies. Recently, the writer noted the similarity between the Colorado Plateau sedimentary geology and that in the Paleozoic red-bed sequence of Nova Scotia and New Brunswick. As a result, prospecting for uranium as well as for copper was initiated, and widespread evidence of uranium occurrence was

found. Such correlation could have little meaning on a magmatic-hydrothermalist theory, nor could the widespread similarity of the red-bed coppers themselves.

The above are merely instances of the numerous correlations that exist between sediments and ore. There are similar correlations between granitized basic volcanic belts and copper provinces, and between chloritized, carbonated greenstone belts and gold provinces. Granitized basic igneous rock belts may produce copper and copper-nickel provinces. Altered peridotites may produce asbestos and also nickel sulfides; but generally, the peridotites must be altered.

A belt of Huronian sedimentary iron-formation will produce an iron-ore province; but there is no province either without the iron-formation source rock, or without subsequent concentration. In some cases this concentration may be due to meteoric waters (lateral secretion in the original sense), but, in other instances, thermal and metamorphic processes may well have played a part.

On the other hand, ore is associated with granitic cupolas, with some basic igneous intrusives that have not been granitized and with volcanoes (15). As already suggested, the emplacement of primary ore is quite closely associated with thermal gradients and with heat foci. The formation of granite is the most important single process associated with the concentration of ore, and, in the writer's opinion, the original reasoning on cupolas is essentially valid. Hot dykes are planes along which ore can move readily; no movement occurs below certain critical temperatures. Additionally, basic igneous rock bodies of substantial dimensions can themselves supply considerable quantities of endogenetic elements such as Pt, Ni and Cu. Regarding volcanoes, the observable evidence suggests strongly that the heating of a large mass of rock beneath a volcano distills off many of the thermally unstable elements and compounds, including sulfur and many of the elements that normally combine with sulfur. These may later be concentrated as important ore deposits.

In the writer's opinion, however, none of these facts make it necessary to conclude that all ore materials travel in a watery solution; nor do they invalidate the concept that heat, temperature, pressure, and concentration are dominant factors governing the reactions leading to the concentration of ore.

The hydrothermal classification of ore deposits and of metalliferous provinces implied that all ores came from great depth, and that the rock associated with them have little significance except in such terms as permeability, porosity, competency, etc. It tends to delete the important associations between certain sedimentary facies and some types of ore; between copper, nickel and basic igneous rocks; and numerous other associations. Significantly, prospectors were not too interested as to whether a deposit is hypothermal or leptothermal. By contrast, the words "native copper in balsalts," "copper-nickel ores associated with basic igneous rocks," "asbestos in serpentine," "red bed copper ores," "copper ores in deltaic sediments," "gold in pebble conglomerates," "greenstone belts with gold ores" convey meanings of great practical importance and must also have genetic significance.

Gangue Minerals

In the present paper, the author set out, principally, to attempt to throw light on the factors that might govern the stability of the valuable minerals found in ore deposits. However, the following observations on calcite seem relevant.

In the Mount Isa district of Queensland, calcite is sought as a flux for smelting. Experience has shown that the calcite bodies are confined to limestone belts that have undergone metamorphism. In zones of structural weakness such as faults or drag folds, relatively pure recrystallized calcite has collected in mineable quantities. In places, the calcite contains up to one percent copper as chalcopyrite. This appears to be a case of calcite concentration by thermal processes in structurally favorable loci.

Again, in the Wilberforce district, Ontario, uraninite has been found near the contact of limestone and younger granite paragneiss. Near the contact, calc-silicate minerals have been formed extensively, and between this zone of alteration and the fresh marble is a shattered zone filled largely with coarse calcite. Apatite is also present in considerable quantities and the uraninite is found mostly in this zone. The calcite appears to have been mobilized by the heat accompanying the formation of granite-gneiss. The extensive and important "carbonatite" deposits, commonly associated with volcanic heat foci, and characterized by abundant calcite, may also result from the thermal mobilization of calcite and other thermally unstable compounds.

CONCLUSION

This paper is meant to suggest directions of thought along which, perhaps, a different approach to the subject of ore deposits could be made.

It is considered that only partial solutions can be suggested at this time and it is important to keep the debate open. Assumptions that ore-genetic problems had been solved were unrealistic, and are not now so widespread.

As suggested by McKinstry (15), experimentation to test concepts would be of great value. Probably, thermal stability and thermal reaction studies could be made in a laboratory. The imposition of large electrical potential differences might speed up the movement of particles and bring time factors within the range of human observation. The effect of various catalysts could be determined. Much fundamental research may have been unrewarding because of the assumption that the magmatic differentiation hydrothermal solution theory was self-evident.

ACKNOWLEDGMENTS

The manuscript was read by Dr. Hans Ramberg and by Dr. H. E. McKinstry. Permission to publish was granted by the Kennecott Copper Corporation of New York. The considerable secretarial work connected with the preparation of a scientific paper was kindly carried out by Mrs. M. G.

McCamus. The above assistance is gratefully acknowledged. The views expressed are entirely the responsibility of the author.

KENNCO EXPLORATIONS, (CANADA) LIMITED,
25 KING STREET WEST,
TORONTO, ONTARIO, CANADA,
Aug. 10, 1956

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STRUCTURAL CONTROL OF URANIUM ORE AT THE MONUMENT NO. 2 MINE, APACHE COUNTY, ARIZONA[1]

TOMMY L. FINNELL

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ABSTRACT

The Monument No. 2 uranium-vanadium deposit is in Monument Valley, Apache County, northeastern Arizona. The uranium and vanadium minerals are in sandstone and conglomerate of late Triassic age, the Shinarump member of the Chinle formation that fills an ancient stream channel cut through the Moenkopi formation of Triassic age and the Hoskinnini tongue of the Cutler formation into the DeChelly sandstone member of the Cutler formation of Permian age.

Tyuyamunite, carnotite, becquerelite, corvusite, hewettite, metahewettite, rauvite, and uraninite are the principal ore minerals. They impregnate sandstone, fill fractures, and replace quartz, clay, and fossil plant fragments.

The structural features lead to the interpretation that, during the Laramide orogeny in Late Cretaceous or Early Tertiary time, movement along the bedding planes brecciated the channel-filling sediments. Resistance of the thicker channel sediments to the bedding plane slippage set up stresses that formed a zone of en echelon strike-slip vertical faults along the channel. The ore-bearing solutions may have risen along the vertical faults from a deep source, and spread out to deposit ore in the highly permeable brecciated sandstone and conglomerate. Further upward movement of the solutions would have been retarded by the lenticular, relatively impermeable clayey siltstone that overlies the ore deposit.

If this hypothesis is valid, zones of en echelon strike-slip faults cutting post-Moenkopi sedimentary rocks in Monument Valley may be an indication of buried channels and of ore deposits within the channels. Additional tectonic studies in the area are recommended to test the structural interpretation.

[1] Publication authorized by the Director, U. S. Geological Survey.

INTRODUCTION

THE Monument No. 2 mine, approximately 7½ miles north of Dinnehotso, Apache County, Ariz. (Fig. 1), is accessible by a graded dirt road leading south from Utah Highway 47, and by a graded dirt road leading west from Shiprock, N. Mex.

During August and September 1951, part of the Monument No. 2 mine was mapped on a scale of 1 inch to 20 feet by Donald H. Johnson and the author on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission, as part of a comprehensive study by the Geological Survey of the geology and uranium deposits in the Monument Valley area.

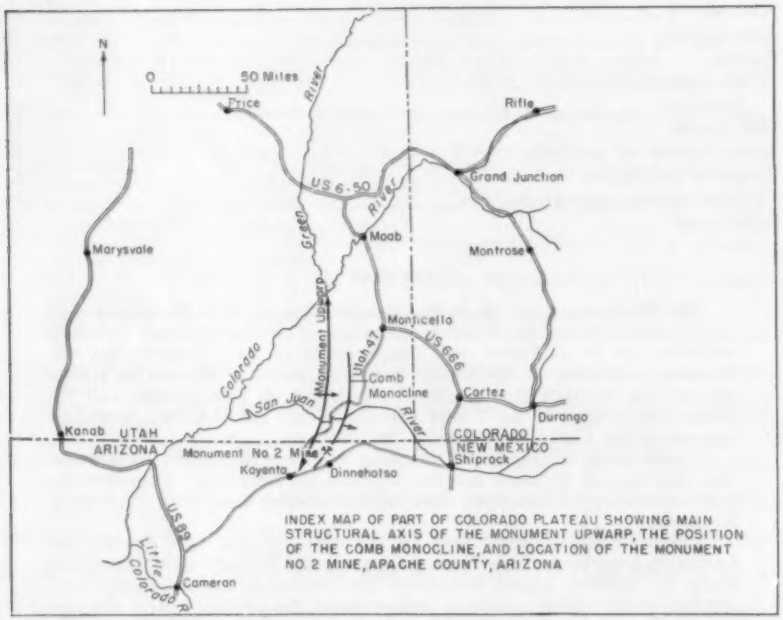


FIG. 1. Index map of part of Colorado Plateau showing main structural axis of the Monument upwarp, the position of the Comb monocline, and location of the Monument No. 2 mine, Apache County, Ariz.

D. W. Viles, vice president in charge of production, and Carl Bell, mine foreman, both of the Vanadium Corp. of America, furnished mine maps and gave permission to enter the mine during the mapping.

GEOLOGY

The Monument No. 2 mine is on a sandstone-capped eastward-dipping cuesta on the southeast flank of the Monument upwarp. It is in the Monu-

ment Valley part of the Navajo section of the Colorado Plateau physiographic province (3). The area is dissected into isolated mesas and serrate cuestas and hogbacks.

Sedimentary rocks near the mine range in age from Permian to Triassic and consist of buff fine-grained crossbedded sandstone, buff and reddish-brown sandstone and shale, and light-gray medium- to coarse-grained and conglomeratic sandstone. The beds have been folded to form the southeast flank of the Monument upwarp. They strike N 9°–14° E and dip 5°–6° SE.

STRATIGRAPHY

Sedimentary rocks that crop out in the near vicinity are, in ascending order, the DeChelly sandstone member and the Hoskinnini tongue of the

FIG. 2. South part of the Monument No. 2 channel. *S,* Shinarump member of the Chinle formation; *M,* Moenkopi formation and Hoskinnini tongue of the Cutler formation; *D,* DeChelly sandstone member of the Cutler formation. Fracture extends upward from the canyon floor through the Shinarump. Comb Ridge in background.

Cutler formation of Permian age, the Moenkopi formation of Early and Middle (?) Triassic age, and the Shinarump member of the Chinle formation of Late Triassic age.

The DeChelly sandstone member of the Cutler formation comprises about 550 feet of buff calcareous micaceous crossbedded very fine- to fine-grained sandstone (Witkind, I. J., personal communication, 1953). Only the upper 150 feet of the DeChelly is exposed below the Monument No. 2 mine. The DeChelly sandstone member conformably underlies the Hoskinnini tongue of the Cutler (Fig. 2).

Near the Monument No. 2 mine, the Hoskinnini tongue of the Cutler formation comprises 8 to 10 feet of light-buff and reddish-brown calcareous crossbedded fine- to medium-grained sandstone with interbedded dark-red thin-laminated siltstone. A dark-red thin-laminated siltstone bed as much as 1 foot thick commonly separates the sandstone of the Hoskinnini from the underlying DeChelly sandstone member. The Hoskinnini seems to be conformable beneath the Moenkopi formation.

The Moenkopi formation of Early and Middle (?) Triassic age is about 25 to 30 feet thick and consists of dark-reddish-brown thin-laminated siltstone interbedded with light-reddish-brown and buff ripple-laminated very fine- to fine-grained sandstone. The contact between the Moenkopi and the overlying

FIG. 3. Fault zone in DeChelly sandstone member below the north part of the Monument No. 2 channel. *S*, Shinarump member of the Chinle formation; *M*, Moenkopi formation and Hoskinnini tongue of the Cutler formation; *D*, DeChelly sandstone member of the Cutler formation.

Shinarump is unconformable, and the Hoskinnini and Moenkopi were completely removed by erosion along the axis of the Monument No. 2 channel before the Shinarump was deposited (Fig. 2).

The Shinarump member of Late Triassic age is the principal ore-bearing unit in the Monument Valley area. At the Monument No. 2 mine, the Shinarump comprises 40 to 60 feet of light-tan and light-gray crossbedded medium- to very coarse-grained sandstone and conglomeratic sandstone with interbedded lenses of conglomerate and clayey siltstone. Conglomerate pebbles are quartz, quartzite, chert, silicified wood, claystone, siltstone, sandstone, and silicified limestone. Silicified logs and carbonized wood fragments are locally abundant in the mine.

STRUCTURE

The Monument No. 2 mine is on the east flank of the Monument upwarp. Strata at the mine strike N 9°–14° E and dip 5°–6° SE. Dips steepen to 20°–25° SE in the Comb Ridge monocline about 1 mile east of the mine (Fig. 1). The Monument upwarp was formed during the Laramide orogeny in Late Cretaceous or early Tertiary time according to Hunt (5) and Eardley

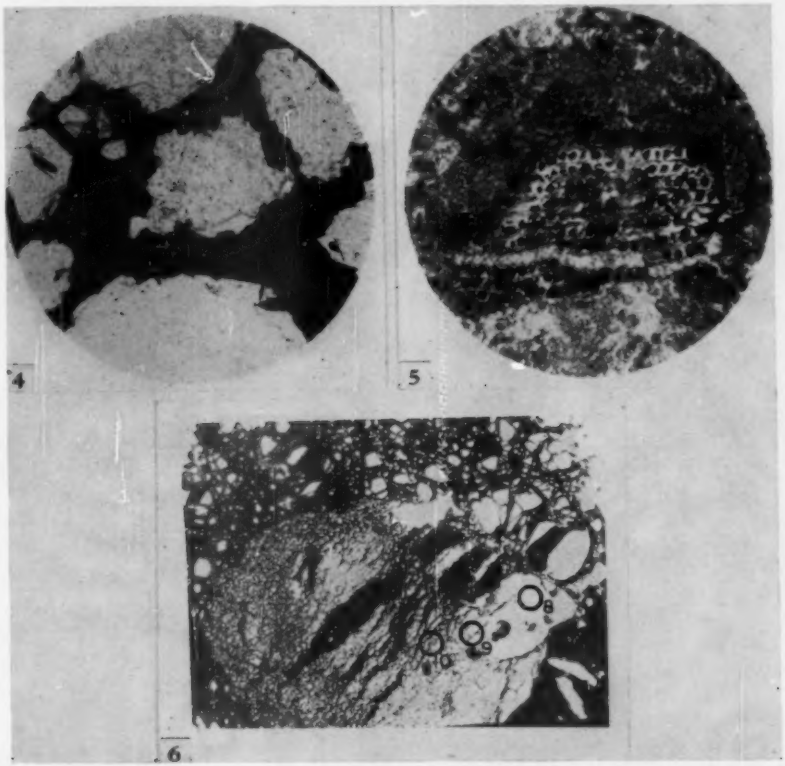


FIG. 4. Photomicrograph of mineralized sandstone of the Shinarump member. Gray detrital quartz and clear secondary quartz overgrowths on the detrital grains are all embayed by opaque vanadium oxides and uranyl vanadates. Plain light, × 54.

FIG. 5. Photomicrograph of fossil plant cell structure preserved by uranium minerals and pyrite. Pyrite and uraninite fill the pore spaces, and uranophane and becquerelite form the cell walls. The plant fragment is enclosed in a mixture of uranium minerals and chalcedony. Plain light, × 54.

FIG. 6. Photomicrograph of a sheared sandstone pebble in brecciated sandstone of the Shinarump member. The open spaces formed by the brecciation are filled with ore minerals. Numbered circles indicate areas shown in Figures 7, 8, 9. Plain light, × 4.

(1). Hunt states, "In Paleocene time *** folding, *** progressed eastward to the Plateaus. The northwest trending Circle Cliffs uplift was formed, and apparently fully so, because its folded rocks are truncated by nearly horizontal, early Eocene, lake beds (Flagstaff limestone). A volcanic highland, probably

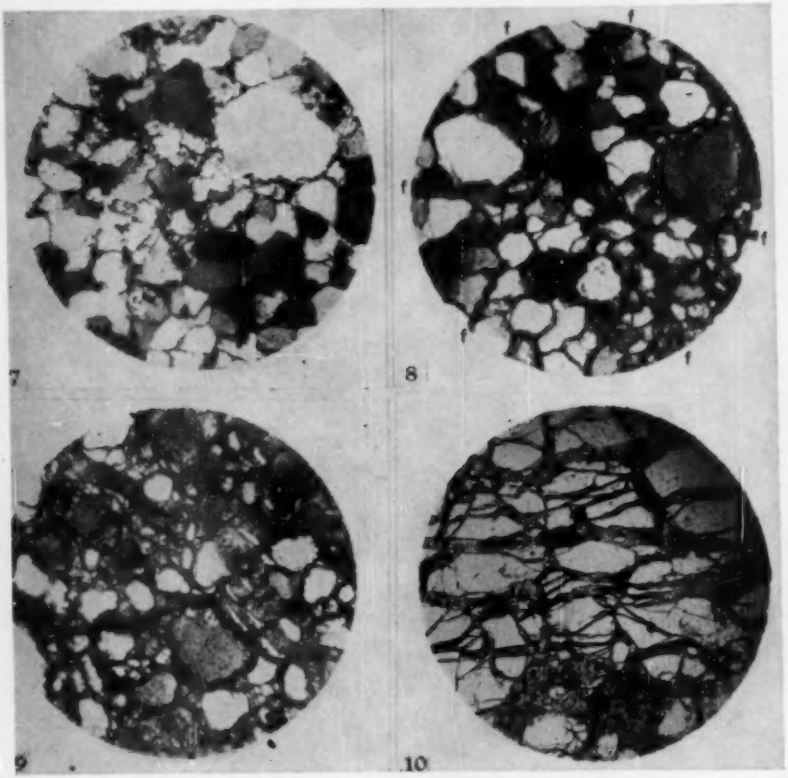


FIG. 7. Photomicrograph of portion of sandstone pebble within circle 8, Figure 6. The intergranular spaces are filled with secondary quartz and some ore minerals. ×-nicols, × 54.

FIG. 8. Photomicrograph of portion of fractured sandstone pebble within circle 9, Figure 7. Fractures, *f*, cut the pebble. The shearing stresses have rolled the quartz grains, forming additional space for ore deposition. Ore minerals fill the fractures and the intergranular spaces. ×-nicols, × 54.

FIG. 9. Photomicrograph of intensely fractured portion of sandstone pebble within circle 10, Figure 7. Parallel extinction between fragments of quartz grains indicates little disturbance of the grains after they were fractured. Ore deposition probably kept pace with void formation, and quartz solution seems to have ceased when ore deposition ceased. ×-nicols, × 54.

FIG. 10. Photomicrograph of brecciated sandstone of the Shinarump member. Fractures are filled with intergrown uranophane and becquerelite. Plain light, × 18.

accompanied by upwarping, formed in the San Juan Mountains and shed volcanic sediments onto the Plateau Province (Animas formation).***"

"Presumably the other folds within the Plateaus also began forming at this time. These include the San Rafael Sweil, Uncompahgre Plateau, and the Monument, Kaibab, Defiance, and Zuni upwarps." More precise dating has not beeen established in the Monument No. 2 area.

Prominent joints in the area trend N 35°–65° W and are essentially vertical (Fig. 2). Many of the joints overlap to form en echelon zones. Differential stresses have induced horizontal displacement along some of the joints. Thus, many joints are now slickensided faults, and pebbles have been displaced as much as 6 inches laterally. Two fault zones can be traced as much as 150 feet vertically into the DeChelly sandstone member below the Monument No. 2 channel (Figs. 2, 3), but their extension below the canyon floor is not known. Strike-slip along several faults cut by the mine workings was measured and reported by Witkind and others (1953, personal communication). Observed displacements in all places are left lateral; along the northwesterly trending faults, the southwest block moved southeast relative to the northeast block. The faults may be barren of uranium minerals, but commonly their surfaces are coated with quartz gouge and tyuyamunite.

In addition to the faults, micro-brecciation of quartz grains is common in ore specimens. Thin and polished sections show fragments of shattered quartz grains completely isolated from each other by ore minerals. Adjacent fragments of some grains have matching edges, and commonly such matching fragments extinguish simultaneously when rotated in polarized light, indicating only insignificant rotation of the fragments during the brecciation (Figs. 6–10). Close-spaced fractures give the ore a layered structure that resembles the annular rings of wood. Brecciated sandstone seems to be the rock that was most favorable for ore deposition in the Monument No. 2 channel; nonbrecciated sandstone is commonly barren or contains uranium concentrations below ore grade.

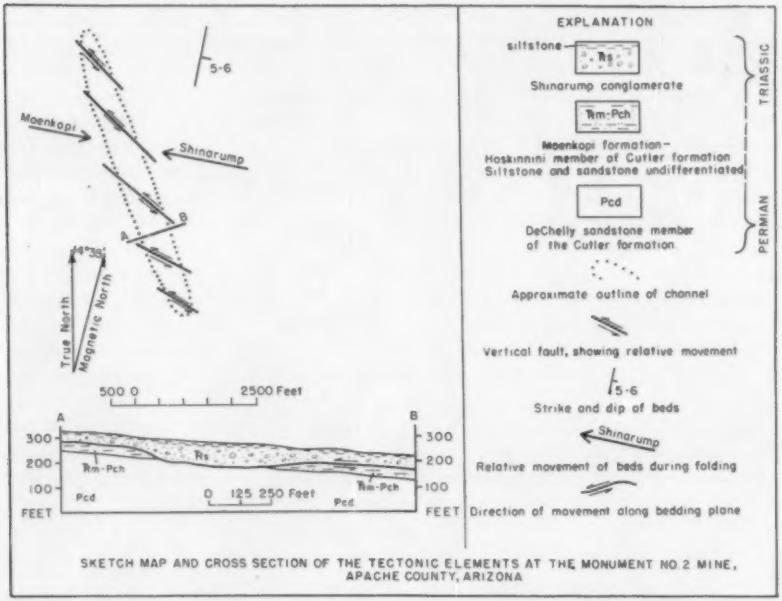
ORE DEPOSIT

The Monument No. 2 mine is in a post-Moenkopi Triassic stream channel that was cut through the Moenkopi formation and the Hoskinnini tongue of the Cutler formation into the DeChelly sandstone member of the Cutler. The channel is about 700 feet wide and as much as 55 feet deep (Figs. 2, 11). The sandstone and conglomerate of the Shinarump that fills the channel contains most of the ore, but the sandstone of the DeChelly in the channel floor locally contains ore along bedding planes and in fractures. All of the known ore is stratigraphically below a lenticular clayey siltstone in the Shinarump. Most of the clayey siltstone zone was eroded away during the Cenozoic era.

Tyuyamunite, carnotite, becquerelite, corvusite, hewettite, metahewettite, rauvite, navajoite, and uraninite are the principal ore minerals in the Monument No. 2 mine according to D. H. Johnson (oral communication); according to Weeks and Thompson (11) fourmarierite, steigerite, and metazeunerite also are present. The ore minerals impregnate sandstone (Fig. 4), replace fossil plant fragments (Fig. 5), replace clay and quartz, and fill fractures in

sandstone (Figs. 6–10). Uraninite filling fractures in quartz grains is illustrated in a descriptive report by Rosenzweig, Gruner, and Gardiner (8).

The ore typically forms flat-lying tabular bodies and rods (the "logs" of the miners) that are concentrated in two distinct levels, one on the channel floor and the other about 25 feet above the channel floor. According to Witkind (1954, written communication), rods are ". . . crudely ovate, flattened, elongate, cylindrical bodies . . . ," and many rods are bounded by roughly circular fracture zones that end abruptly near the edge of high-grade ore.



SKETCH MAP AND CROSS SECTION OF THE TECTONIC ELEMENTS AT THE MONUMENT NO. 2 MINE, APACHE COUNTY, ARIZONA

FIG. 11. Sketch map and cross section of the tectonic elements at the Monument No. 2 mine, Apache County, Ariz.

Age determinations made by Stieff, Stern, and Milkey (9) indicate that the carnotite-type ore is about 75 million years old. The uranium emplacement in the Monument No. 2 mine thus seems to be contemporaneous with or later than the time of deformation. The deformation was probably during the Laramide orogeny which began in Late Cretaceous time, more than 60 million years ago according to Marble (7).

INTERPRETATION OF STRUCTURE

The faults and breccia at the Monument No. 2 mine are thought to be caused by components of tectonic stresses along the channel when the Comb

monocline and the Monument upwarp were formed. During the folding, the wedge of Shinarump in the Monument No. 2 channel pushed against the updip channel bank because of the tendency of the Shinarump to slide over the relatively incompetent Moenkopi toward the crest of the Monument upwarp (Fig. 11). This relative movement along bedding planes, indicated on the cross section in Figure 11, is like the relative movement between individual cardboards in bent cardboard stacks described by Van Hise (10). The maximum relative displacement along bedding planes in parallel folding can be calculated from the formula suggested by Earp (2). The formula is $R = \frac{Pi \times p \times T}{180°}$ where R is the relative displacement along bedding planes, p is the number of degrees through which the beds have been rotated, and T is the thickness of the beds involved in the folding.

If all the adjustment to folding in the Shinarump was concentrated along the Shinarump-Moenkopi contact, the relative movement between the two units at the Monument No. 2 mine is about 5 feet, a small but perhaps significant amount. The relative movement along the northwesterly trending faults seems to represent expansion in the direction of least stress to relieve pressure at the channel bank. During the adjustment between the Shinarump and the older rocks, the brecciation of the channel sediments and of the hummocks of DeChelly on the channel floor probably occurred. Brecciation was probably strongest in relatively competent features such as fossil logs and strongly cemented sand lenses and concretions.

If the preceding interpretation is valid, some similarly situated channels in the Monument Valley area will have structural features similar to those in the Monument No. 2 channel. Channels that trend across local dips are more likely to be brecciated and cut by strike-slip faults than are channels that trend parallel to local dips. Zones of en echelon strike-slip faults cutting the Shinarump and rocks overlying the Shinarump on the flanks of anticlines or near the crests of monoclines may indicate hidden channels. Critical observation and careful geologic mapping on a large scale will be required to delineate these fault zones.

ORIGIN OF THE DEPOSIT

The uranium and vanadium ore at the Monument No. 2 mine is associated with faults and breccia that probably originated during the Laramide orogeny. The faults, which extend down into the DeChelly (Fig. 2), and perhaps much deeper, may have provided channelways for the solutions that carried the ore metals into the channel sediments. When the solutions reached the channel, they may have spread out and permeated the sandstone and breccia, because upward movement of the solutions might have been retarded by the relatively impermeable clayey siltstone that overlay the channel-filling deposits. The clayey siltstone, shown on the cross section in Figure 4, was perhaps an impounding barrier (6) that may have filtered metallic ions from solutions passing through the barrier so they could be deposited in favorable rock beneath the barrier. Mackay (6) indicates that ore thus localized would not

necessarily be deposited directly beneath the barrier but might be in the first favorable rock below the barrier.

Stieff, Stern, and Milkey (9) interpret the lead-isotope data to suggest that the uranium and vanadium were introduced into the Shinarump during Late Cretaceous or early Tertiary time from a common source, or from similar sources to be found at depth.

If the localization of the uranium and vanadium ore and the formation of the strike-slip faults are genetically related, en echelon zones of strike-slip faults may be guides to mineralized ground along the buried extensions of channels.

CONCLUSIONS AND RECOMMENDATIONS

The Monument No. 2 uranium-vanadium deposit seems to have been localized in brecciated channel-filling deposits of the Shinarump member of the Chinle formation. Brecciation and faulting that produced ore-solution channelways are interpreted to be the result of the Late Cretaceous or early Tertiary folding which formed the Monument upwarp and its east flank, the Comb Ridge monocline. Analysis of the tectonic elements suggests that in Monument Valley, Shinarump-filled channels trending across local dips may be more favorable for ore than are channels trending parallel to local dips. Vertical strike-slip faults may indicate mineralized ground along a projected channel trend, and zones of en echelon strike-slip faults cutting the Shinarump and younger rocks on the flanks of anticlines and near the crests of monoclines may indicate buried channels. Critical observation and careful geologic mapping on a large scale are required to delineate the fault zones adequately.

Application of the structural interpretation should begin with detailed studies of known channels and uranium deposits in the Monument Valley area. If the known channels are found to have structural features similar to those at the Monument No. 2 mine, the structural studies can be extended to places where ore deposits and channels are not exposed.

Perhaps the first place to test the interpretation should be on Comb Ridge, along the southeasterly projection of the Monument No. 2 channel, where R. E. Thaden (oral communication) observed northeasterly trending joints with left lateral strike-slip displacement. If mapping there reveals a zone of en echelon strike-slip faults similar to the zone along the Monument No. 2 channel, suggesting a large channel at depth, a modest drilling program might be warranted.

This preliminary work suggests that careful study and interpretation of local tectonic structures on the Colorado Plateau may be of value in explaining the localization and form of the uranium deposits and in searching for new deposits. A careful analysis of the tectonic features in a mining district is perhaps justified by Fowler's observation (4) concerning the Tri-State district where he demonstrated that the ore is closely related to areas of tectonic disturbance, and that little or no ore is present where the beds are relatively undisturbed. Fowler (4) states:

". . . after the initial discovery, the drilling of 600 holes under informed geologic guidance, in lieu of the 30,000 actually drilled, could have prospected an area of 37 square miles sufficiently to define the mining area and many important features in and around it."

U. S. GEOLOGICAL SURVEY,
DENVER, COLORADO,
July 19, 1956

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DISTRIBUTION OF SECONDARY URANIUM MINERALS IN THE W. WILSON DEPOSIT, BOULDER BATHOLITH, MONTANA[1]

H. D. WRIGHT AND D. O. EMERSON

ABSTRACT

Weathering of pitchblende in the "siliceous reef" deposit at the W. Wilson mine, near Clancy, Montana, has produced an assemblage of secondary uranium minerals, including meta-autunite, meta-uranocircite, meta-torbernite, meta-zeunerite, uranophane, beta-uranophane, phophuranylite, gummite, and an unidentified mineral, possibly a complex uranium silicate. The secondary minerals show a distinct zonation about primary uranium concentrations. Variation in composition of the groundwater solutions with depth, together with the differences in solubility of the secondary minerals, may be responsible for the zonation. Vitreous orange and yellow gummite replaced pitchblende directly, and a fine-grained yellow mixture of oxides, silicates and phosphates of uranium (called "gummite" in the field) was deposited in the vein and wall rock breccias around the pitchblende. Meta-autunite and some meta-uranocircite were deposited farther out from pitchblende in the intergranular pore spaces of the wall rock. Meta-torbernite and meta-zeunerite tend to be concentrated along fractures at considerable depths below the surface, due, it is thought, to the probable higher concentration of copper in the solutions with increasing depth.

The apparent deposition of the bulk of the uranium secondaries within a short distance from the primary source, pitchblende, appears to indicate that supergene enrichment in the oxidation zone is not important. The sparse distribution of sulfides in the siliceous veins and the apparent lack of other strongly reducing conditions below the water table would seem to render unlikely the possibility of a pitchblende enrichment by reduction of the U^{6+} ion in meteoric water moving downward below the water table.

INTRODUCTION

THE W. Wilson mine, 15 miles south of Helena, Montana, is the largest of several small uranium producers in the northern part of the Boulder batholith. It has developed a group of small but rich pods of uranium ore along a "siliceous reef" vein deposit. Lying between the water table and the surface, the pitchblende in these orebodies has been almost completely transformed into a group of brightly colored and generally well crystallized secondary uranium minerals. The closely-spaced network of recent mine workings provided an exceptional opportunity to study the occurrence and distribution of these minerals in a sulfide-bearing hydrothermal vein deposit. Of particular interest was the distribution and zoning of the secondaries relative to the location of primary pitchblende, the land surface, and the ground water table.

[1] Contribution No. 56–7, College of Mineral Industries, The Pennsylvania State University, University Park, Pennsylvania.

Field study was begun during the summer of 1952 as part of a program of mineralogical studies of vein uranium deposits in the Boulder batholith, undertaken at The Pennsylvania State University on behalf of the U. S. Atomic Energy Commission. A summary of the crystallographic, optical, X-ray, and chemical data on the secondary uranium minerals and a description of the methods used in their identification will be presented in a separate paper.

Topography.—The discovery trenches of the W. Wilson mine were sunk along a siliceous reef at the crest of a low ridge trending N 60° E. They lie at an elevation of 4,605 feet. The characteristic rounded hills and ridges, formed from the jointed granitic rocks of the batholith on weathering, rise to about 5,500 feet, 1,000 to 1,500 feet above the valley floors. The area is about 15 miles east of the Continental Divide and is characterized by semi-arid climate, with an annual precipitation of 15 to 20 inches.

GEOLOGY OF THE W. WILSON MINE

The siliceous reef containing the deposits worked by the W. Wilson mine crops out over a distance of about 2,000 feet. The easternmost 500 feet of this is abnormally radioactive, and secondary uranium minerals may be seen at places along the outcrop. The main silicified zone, five to six feet wide, trends N 60° E and is nearly vertical. Small spurlike silicified zones branch from the main zone on the south side and trend eastwardly.

Meschter (2) and Bieler (1) have described the veins and their structure. The veins form a complex anastomosing pattern with as much as four feet of wall rock lying between major segments of the vein. Individual veinlets range from a fraction of an inch to several inches in thickness, widening rarely to a foot or more. Microcrystalline quartz forms the major part of the vein material. Microscopic inclusions of pyrite, galena, sphalerite, tetrahedrite, argentite, pitchblende, chalcopyrite, and covellite are scattered through the quartz, giving it a color ranging from light gray to black. Pitchblende also occurs in pods in the silicified wall rock next to the veins. Secondary uranium minerals are found both in scattered patches in the vein proper, and disseminated through the wall rock.

The veins are enclosed by an envelope of rather severely altered wall rock extending as much as six feet on either side of the vein zone. From the margin of the alteration envelope inward toward the vein, successive zones representing increasing intensity of alteration are characterized by montmorillonite, kaolinite, and sericite-microcrystalline quartz. The zones are gradational and in places some are missing altogether. The lack of sericite development along much of the vein zone is taken to indicate somewhat less severe alteration than that accompanying many mesothermal deposits, and suggests that the veins belong in either the low temperature portion of the mesothermal or high temperature epithermal range of Lindgren. The abundance of open space filling in veins and vugs suggests a low pressure environment of deposition at no great depth beneath the surface.

Several periods of fracturing before and after mineralization are recog-

nized. The most persistent fractures are nearly horizontal joints or sheets. These are coated with limonite and in places contain aragonite, hyalite and common opal, and secondary uranium minerals.

All workings of the W. Wilson mine except the main drift and part of the adit on the President level are above the present water table. There is considerable moisture in the fractures of the upper levels. A moderate amount of water drips from the back and walls of the deepest President level workings.

Mine Development.—Although the closely spaced mine workings provided many excellent exposures for sampling and study, the distribution of the workings placed definite limitations on the study of secondary uranium mineral distribution. For this reason it is thought desirable to include the following information on the mine workings. Following the sinking of two trenches near the crest of the ridge in 1951, the 150 foot W. Wilson adit was driven from a point on the hillslope 125 feet vertically below the trenches, and drifts were cut westward along two vein systems. There are about 120 feet of workings in the No. 2 drift, and a 30 foot raise connects it with the surface. At a point 360 feet westward along the 500 foot No. 1 drift, a vertical raise was driven to meet the west end of the north trench. From this raise several intermediate levels have been cut and the bulk of the ore has been taken from the drifts and the stopes of these intermediate levels. The sub-levels are at 30, 50, 70, and 95 feet below the surface and contain 170, 50, 95, and 60 feet of drifts respectively. Several crosscuts have been made and an inclined raise from the 120 foot level to the surface has been completed. The President adit meets the vein system about 250 feet below the open trenches. Two drifts, 60 feet and 120 feet long, and a 140 foot crosscut explore the major vein structures on this level.

Previous Studies of the Secondary Uranium Minerals.—In the course of detailed mapping of the area in the vicinity of the W. Wilson deposit, Roberts and Gude (3) reported the occurrence of rutherfordine, uranophane, volgite, torbernite-zeunerite, autunite-uranocircite, and gummite in the outcrop of the reef now being developed by the W. Wilson mine. Thurlow and Reyner (4) noted the presence of autunite, torbernite, gummite and possibly zeunerite, phosphuranylite, and uranophane in the open cuts along the reef.

Meschter (2) found meta-torbernite, meta-zeunerite, autunite, uranophane, gummite, uranocircite, and phosphuranylite in the underground workings, and noted that these minerals were distributed in three crude zones. Gummite and phosphuranylite were reported to occupy the innermost zone, in close association with pitchblende. Uranophane, autunite, and uranocircite were deposited in an intermediate zone somewhat farther from pitchblende. The outermost zone is represented by meta-torbernite and meta-zeunerite.

FIELD STUDY AND SAMPLING

Field study of uranium deposits and prospects in the northern part of the Boulder batholith was conducted during the summers of 1952, 1953, and 1954 by the present authors together with B. H. Bieler (1953, 1954) and W. P. Shulhof (1953). Field data and samples of the secondary uranium minerals

in the W. Wilson mine were collected for laboratory study during 1952, and were augmented by additional information and material as development of the mine, especially on the intermediate levels, continued during 1953 and 1954. During 1954 the President adit had intersected the W. Wilson vein system and for the first time exposed W. Wilson vein material below the water table. No secondary uranium minerals were observed below the present water table. Accurate mapping of the distribution of secondaries in the mine was not possible because they were largely obscured in the dust-covered workings, and because optical examination, at the minimum, is necessary for even tentative identification of some species.

A near-vertical, tabular cavity two to three feet wide and about 20 feet long extends from the surface to the 95 foot sub-level. This exposure together with the drifts on the various levels provided ample opportunity for sampling in the plane of the vein structure, but the study of secondary uranium distribution outward from veins was considerably restricted as crosscuts exposing the vein walls are rather few. In the drifts the walls of the veins cannot be examined at distances greater than three to four feet from the vein. In the places where the wall rock can be studied outside these limits very few secondaries have been observed. The impression is gained that the secondaries do not extend in appreciable quantity far from the vein.

Certainly many factors have determined the distribution of the secondary minerals, such as depth below the surface, position of the water table, distance from primary uranium ore, trend of channels for the solutions, favorable sites for deposition, and the pH and chemical makeup of the groundwater solutions. However, due to the irregular and sparse distribution of the secondaries, actual sample locations were determined chiefly by the available exposures.

Three types of sample suites were collected from the mine: 1) a vertical section sample in the plane of the vein zone, 2) horizontal section samples across veins, and 3) individual "spot" samples.

A group of 25 samples were collected at two to three-foot intervals as close as possible to a near vertical line from the 30 foot to the 70 foot sublevels. Additional samples along an offset line extended this section to the 95 foot level. Throughout the section the distance from the vein varied from zero to about three feet. The vertical section provided material for a study of the most radioactive sites near the vein structure from about 20 to 90 feet below the surface.

Fourteen section samples across veins or fractures were obtained. A continuous series of samples spaced from three to twelve inches apart was taken across the face or back of the drifts. The sections generally were continued to the drift wall or stopped at barren rock. In general, the more abundant concentrations of secondaries were sampled in this manner.

Finally, to represent more completely the distribution of secondaries in the mine, spot samples were taken from scattered locations where secondaries were abundant enough for satisfactory study. In all, about 225 samples were collected in place for the distribution study, in addition to a large number of specimens from the ore pile for fundamental mineral identification and characterization.

THE URANIUM MINERALS

Primary Uranium Minerals.—Pitchblende is the only uranium mineral recognized as primary. Massive pitchblende occurs in the silicified wall rock in pods up to one and one-half inches in diameter and one-fourth inch thick, as scattered fragments in vein breccias, as thin coatings on fragments of wall rock and microcrystalline vein quartz, and as microscopic inclusions scattered through the microcrystalline vein quartz. Microcrystalline quartz and sphalerite are intergrown with it and there is evidence that some of the sphalerite replaced pitchblende. Oxidation and hydration have altered the outer portions of most of the megascopic pitchblende grains, and many of the colloform masses have been completely replaced by secondary minerals. Although all of the uranium is thought to have been deposited originally as pitchblende, nearly all of it is now in the form of secondaries and pitchblende is rarely observed.

Secondary Uranium Minerals.—Preliminary to a systematic study of the distribution of the secondary uranium minerals, careful determinative studies were made on all of the species of secondaries found. These studies included optic, X-ray, microchemical, and spectrographic determinations. On the basis of these studies, a set of distinctive criteria enabling rapid and sure identification was selected for each mineral. The basic mineralogic data and determinative criteria are summarized elsewhere.

The minerals identified in samples from the W. Wilson mine are meta-autunite ($Ca(UO_2)_2(PO_4)_2 \cdot 2\frac{1}{2}$–$6\frac{1}{2}H_2O$), meta-uranocircite ($Ba(UO_2)_2(PO_4)_2 \cdot 8H_2O$), meta-torbernite ($Cu(UO_2)_2(PO_4)_2 \cdot 4$–$8H_2O$), meta-zeunerite ($Cu(UO_2)_2(As_2O_4)_2 \cdot 8H_2O$), phosphuranylite ($Ca(UO_2)_4(PO_4)_2(OH)_4 \cdot 7H_2O$), uranophane ($Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$), and beta-uranophane ($Ca(UO_2)_2(SiO_3)_2(OH_2) \cdot 5H_2O$). An unidentified mineral occurring in clusters of fine yellow needles was found at one place in the mine. The X-ray, optical, and spectrochemical data indicate that the mineral is probably a new species, a complex hydrated uranium silicate.

The term "gummite" has been used by other workers in the Boulder batholith, as a field name, to refer to a very fine-grained, yellow mixture of secondary uranium minerals. It has been found to vary widely in composition, containing variable amounts of uranophane, beta-uranophane, and phosphuranylite, together with lesser amounts of unidentified hydrous uranium oxides. For want of a better name, the mixture is referred to by the authors as "gummite," in quotation marks. Closely associated with some of the pitchblende fragments is a glassy orange to yellow material which fits the more conventional description of gummite. It is uncommonly observed in the mine, and no reference is made to it in the distribution sections presented below.

Textural Relationships of the Secondary Minerals.—Several thin sections and polished sections of the ore, some containing pitchblende, and numerous thin sections of the microcrystalline quartz veins and the wall rock were examined for information on the texture and small-scale distribution of the secondary minerals. The minerals are easily located by their color and high relief, but positive identification usually is not possible in thin section. A few

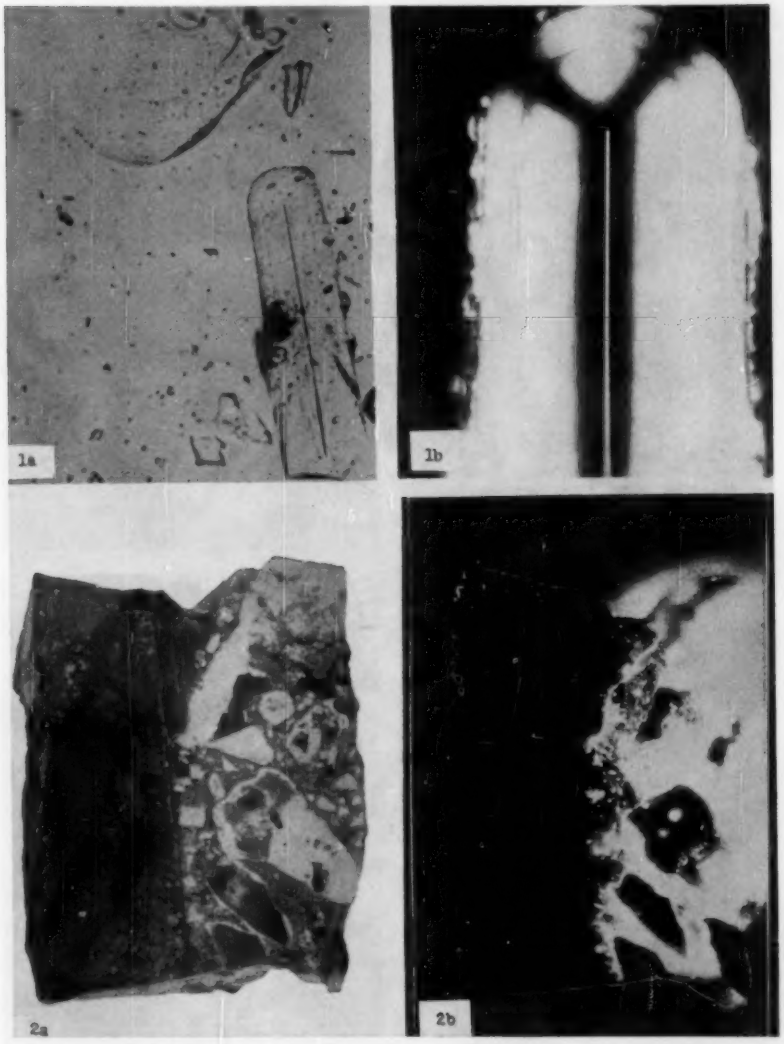

FIG. 1a. Opal, deposited on needle-like crystals of uranophane. The fragment in the upper part of the picture is an end view of a needle with the opal bands around it. Magnified 60 ×.

FIG. 1b. One of the opal fragments magnified 280 times (crossed nicols). The banding and spherulitic extinction are clearly seen.

FIG. 2a. A rock chip, 1½ inches long, which shows vein material on the left and a breccia of vein and wall rock fragments on the right.

FIG. 2b. An autoradiograph of 2a showing the radioactivity concentration around fragments in the breccia and scattered throughout the matrix.

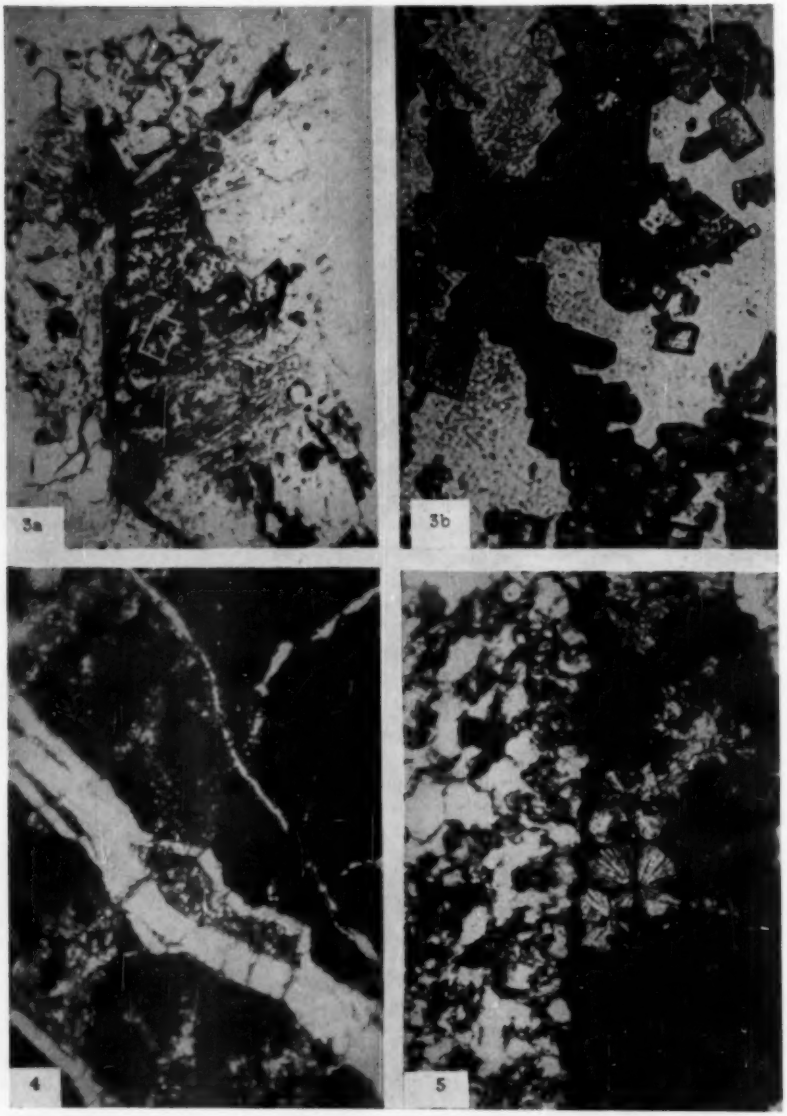

FIG. 3a. The apparently opaque minerals are the high index uranium secondaries which have developed along the boundaries and cleavages of a feldspar crystal. The field of the photograph is 2.3 mm long. Magnified about 35 ×.

FIG. 3b. Detail from within the area marked in Figure 3a. Well developed

veinlets and radiating clusters of uranophane could be identified as such and the orange to yellow gummite is distinctive, but no other identifications were made.

Clusters of uranophane crystals are abundantly developed along the walls of open fractures throughout the mine. The most commonly associated mineral, other than limonite, is opal. The opal generally forms an enclosing crust over the matte of uranophane needles, the banding of the opal conforming to the crystal outlines of the uranophane (Figs. 1a, 1b).

The greatest abundance of secondary minerals is seen in hand specimens to surround rock fragments in the brecciated zones (Fig. 2a). This distribution is illustrated in Figure 2b by an autoradiograph of a sawed slab of the vein and breccia zone. The concentric bands of secondary minerals give some of the ore a pisolitic appearance. Thin sections show that the fine-grained gouge between the breccia fragments is a favorable site for uranium deposition and the fine-grained clay and the feldspar show some replacement by secondaries.

The development of secondary minerals in feldspar is illustrated by Fig. 3a; the outline and cleavage traces of a feldspar grain are lined with secondaries, which are dark in plain light due to high relief. The areas between the cleavage traces are filled with kaolinite, and as may be seen in Figures 3a, 3b, the clay gives way to the development of well formed tabular crystals of secondaries. When this process is carried to completion the mold of the original feldspar grain is completely filled with soft yellow uranium minerals. A similar occurrence of these minerals is found along the cleavage planes of biotite.

Figure 4 shows a veinlet of uranophane cutting across the gummite (translucent) and pitchblende (opaque). These veinlets occur throughout the veins and adjacent wall rock. Crustification takes place on both walls of an open fracture, and radial clusters of crystals develop until they meet near the center of the vein.

Gummite forms pseudomorphs after pitchblende by replacement and good examples of the texture have been seen but are not common. The gummite of Figure 4 appears to have replaced pitchblende, as indicated by residual pitchblende inclusions near the pitchblende-gummite boundaries. In this case the pitchblende is massive and preservation of characteristic texture is not seen. An interesting development of secondaries in sphalerite which had previously replaced pyrite was observed in matching polished and thin sections. The crystal outline of pyrite is preserved and traces of sphalerite are seen in the secondaries which retain the pyrite outlines.

Radioactive limonite veinlets occur throughout the vein system and are

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secondary uranium crystals, concentrated along former cleavage traces of a feldspar. The light gray area is filled with kaolinite. The field of the photograph is 0.18 mm long. Magnified 450 ×.

FIG. 4. Pitchblende (opaque) is partially altered to a glassy yellow gummite (dark gray). Both are veined by uranophane (white). The field of the photograph is 0.8 mm long. Magnified about 100 ×.

FIG. 5. Spherulitic group of uranophane crystals in a limonite vein in microcrystalline quartz. The field of the photograph is 0.8 mm long. Magnified about 100 ×.

favorable locations for secondary uranium minerals. The uranophane cluster in Figure 5 is surrounded by limonite which fills a fracture in a fragment of the quartz vein material.

Secondary Mineral Zoning About a Pitchblende Nodule.—Pitchblende was found in place at only two locations in the W. Wilson mine during field work over three summers. One of these "finds" presented a rare opportunity to study secondary mineral zoning on a small scale. A nodule of pitchblende was encountered as a sample was being cut from limonite-stained, silicified wall rock on the 70 foot sub-level. It was one and one-half inches long, one-fourth inch thick and was oriented parallel to the quartz vein an inch away. A conformable envelope of glassy, deep yellow and orange gummite, about one-fourth inch thick, surrounded the pitchblende. The gummite passed rather abruptly into a lighter yellow, powdery material, less than one-fourth

TABLE 1

SEMI-QUANTITATIVE SPECTROGRAPHIC ANALYSIS OF MINERALS ZONED ABOUT A PITCHBLEND NODULE

Pitchblende	Gummite
>10% U	U
1–10% Si, As, Pb, Ba, Sb, Cu, W	Si, As, Sb, Cu, W
0.1–1% Fe, Al, Ca, Cd, Mo, P	Fe, Al, Ca, Pb, Ba, Mo, P
0.01–0.1% Mn, Ni, Cr	Cd, Cr
0.001–0.01% Mg, Ag, Be, Bi	Mg, Mn, Ag, Be, Bi

Conformable yellow material (chiefly uranophane)	Scattered light yellow material (chiefly uranophane)
>10% U, Si	U, Si
1–10% Cu, P, As, W	Cu, P, As, Sb, W
0.1–1% Fe, Al, Ca, Pb, Ba, Sb, Mo	Fe, Al, Ca, Pb, Ba, Mo
0.01–0.1% Mn, Cd, Cr	Mn, Cd, Cr
0.001–0.01% Mg, Ag, Be, Bi	Mg, Ag, Be, Bi

Meta-torbernite

>10% U, P
1–10% Si, As, Cu
0.1–1% Fe, Al, Ca, Pb, Ba, Sb, Mo
0.01–0.1% Cd, Cr
0.001–0.01% Mg, Ag, Be, Bi

inch across, showing fairly definite boundaries conformable to the pitchblende. Beyond this were scattered pale yellow and bright green tabular crystals, which coated limonite-stained fractures up to six inches or more from the pitchblende. Perpendicular to the tablet the scattered yellow and green crystals were within three-fourths inch of the pitchblende on the vein side and as close as one-half inch on the opposite side. Secondaries were formed over a distance of only one and one-half inches on the vein side of the pitchblende, and about three-fourths inch on the opposite side of the tablet. Limonite, although abundant elsewhere, is absent from the pitchblende and its conformable envelopes of gummite and powdery yellow material.

This sample was collected in three parts for laboratory study: 1) pitchblende and gummite, 2) powdery yellow conformable material, and 3) green and yellow scattered secondaries. Under the binocular microscope the pitchblende showed a bright, submetallic luster, and was free of noticeable im-

purities except dark microcrystalline quartz veinlets. Inclusions of pitchblende extended into glassy orange gummite, which graded outward into glassy yellow material with fewer inclusions. Both the conformable yellow and the scattered light yellow materials were shown by x-ray to be predominantly uranophane. Some phosphuranylite was recognized with the petrographic microscope, but part of the very finegrained material could not be identified optically. The green flakes were found to be meta-torbernite containing a sizeable amount of As and Si.

Table 1 shows the results of spectrographic analysis of the pitchblende, gummite, and the yellow minerals described above. The gummite has a composition similar to that of the pitchblende but with smaller amounts of Pb, Ba, Cd, Mn, Cr, and Ni. The yellow minerals in the envelope conformable with the pitchblende nodule, and those that were scattered around it, have about the same composition and they contain more P, Si, and Mn than the gummite. The remarkable consistency of the composition from pitchblende through the "gummite" zone suggests that oxidation and hydration are the principal chemical processes in the initial alteration of the pitchblende. It was disappointing, however, not to find recognizable lines of hydrous oxides in the X-ray patterns.

DISTRIBUTION OF SECONDARY MINERALS

Data from Section Samples.—Information on the distribution of the uranium minerals was obtained chiefly from study of the section samples taken across veins and fractures and vertically between levels in the mine. The locations of the sections and spot samples, together with a notation of the minerals present, are given in the Appendix. Each sample was examined in the laboratory and the uranium minerals identified by criteria developed in the course of the determinative studies. A systematic procedure for comparison of these samples was followed throughout the distribution study. First, the highest radioactivity reading for the sample given by the portable geiger counter was recorded. These were plotted on a log scale in milliroentgens per hour. Then a check for fluorescence with the ultra-violet light was made and a few grains of the fluorescent minerals checked in an index oil to ascertain if they were meta-autunite, meta-uranocircite, or meta-zeunerite. The non-fluorescent minerals were identified under the binocular microscope, or if still unidentified, material was picked and checked by optics in immersion oils. The amount of each mineral in a sample was estimated and recorded in one of five classes defined as follows:

TT = a grain or two could be seen but not enough to pick for an optical test.
T = enough material for an optical check but less than one milligram needed for an X-ray spindle.
M = enough for X-ray but less than the ten milligrams needed for spectroscopic analysis.
A = enough for spectroscopic analysis; ten to twenty-five milligrams.
AA = more than twenty-five milligrams.

The descriptions and section plots of secondary distribution in the individual section samples are included in Appendix I. A summary of the overall features and some interpretations of factors which may have been responsible for the observed distribution are presented below.

Each of the spot samples was studied in the same manner as the individual samples of the sample sections. The minerals and the amounts of each found are listed in Appendix II, which is arranged by sample location. Each group contains all of the spot samples from one level, and the samples are listed according to location from west to east. In addition, a composite list showing the maximum amount of each mineral in each of the sample sections is included as though the section were one spot sample.

SUMMARY AND DISCUSSION OF THE DISTRIBUTION OF SECONDARY URANIUM MINERALS

As noted previously, the bulk of the primary pitchblende appears to have been deposited adjacent to the veins. "Gummite," in every section containing it, was found as pods and veinlets in the altered wall rock and wall rock breccias, usually within a few inches and never more than one and one-half feet from the veins. Although the original form of the pitchblende generally was destroyed during alteration, it is probable that most of the "gummite" developed in or close to former pitchblende. This relationship is further supported by the abundance of "gummite" in the upper levels, where considerable amounts of pitchblende have been extracted, and its almost total absence from levels below the 70-foot sub-level where pitchblende, other than minute inclusions in the microcrystalline vein quartz, has not been found. The similarity in chemical composition between the "gummite" and the pitchblende indicates that the metals localized in the formation of pitchblende were not appreciably removed, nor were they differentially leached, during initial oxidation and hydration. It also indicates that the "gummite," which forms a large portion of the ore, was deposited only a short distance from pitchblende.

Uranophane, commonly associated with phosphuranylite in the "gummite," occurs in moderate amounts as far as two feet from the vein. Although present on all levels, it is most abundant in the upper parts of the mine and is rarely observed on the other levels. Except near the vein, where it is found in rather tight veinlets in breccia fragments, the mineral crystallizes chiefly in open fractures.

Most of the phosphuranylite identified was found in "gummite"; only small amounts of the mineral were observed to occur alone in a well crystallized form. Where present in the section samples, phosphuranylite occurs in fractures within one foot of the vein.

The other fine-grained yellow minerals of "gummite," as well as uranophane and phosphuranylite, appear to be rather insoluble in groundwater, and were deposited near primary uranium sites. Where they occur more than a few inches from the vein they are found in open fractures.

The members of the meta-torbernite structure group are dispersed over a considerable distance into the wall rock and downward from the upper levels. Plates of both meta-autunite and meta-uranocircite fill voids between grains

of the altered wall rock as far as four and one-half feet from the vein. In about two-thirds of the sections, meta-autunite has the greatest range horizontally of all of the secondaries. While the vertical ranges of deposition of meta-autunite and meta-uranocircite are similar, that for uranocircite is a little lower. Meta-autunite occurs in the open trenches, while meta-uranocircite is absent. Further, meta-uranocircite is found in open fractures below the 70-foot sub-level, which is the lower limit of the meta-autunite distribution.

In the upper levels, meta-zeunerite occurs in trace amounts near the veins. Its distribution outward from the veins becomes wider in the lower levels: meta-zeunerite is found two feet from the vein on the 95 foot sub-level and as far as ten feet away on the 120 foot level. In each occurrence the crystals of meta-zeunerite were deposited in open fractures.

Meta-torbernite, which is not common in the W. Wilson deposit, also formed in the open fractures. Although found on the 30, 70, and 120 foot levels it occurs in only eight samples (cf. Appendix II), all of them rather close to veins. It is associated with meta-zeunerite or gummite in the upper levels and occurs alone only on the 120 foot level.

CONCLUSIONS

Detailed study of the distribution of the secondary uranium minerals in the W. Wilson deposit has revealed a distinct zonation relative to the land surface and to deposits of primary uranium in the form of pitchblende. It is apparent from the nature of the zoning and the absence of secondaries below the water table that the redistribution was accomplished by meteoric water in the zone of oxidation. The factors responsible for the observed distribution are complex and the pattern is not completely understood, but certain inferences can be drawn.

It is interesting to note, in connection with the similar occurrence and distribution of meta-autunite and meta-uranocircite, that the analysis of meta-uranocircite shows a large calcium content. The explanation for the difference in distribution of these two calcium-bearing minerals and the copper-bearing meta-torbernite and meta-zeunerite is believed to lie in the different sources of the metallic elements associated with uranium in these minerals. It seems probable that a considerable amount of calcium is available in the groundwater which has percolated through the altered rock adjacent to the vein and leached the remnants of plagioclase not destroyed during the hydrothermal alteration. The source of copper in the meta-zeunerite and meta-torbernite, and arsenic in the meta-zeunerite, is in the ore minerals of the vein—chalcopyrite and tetrahedrite, chiefly.

It is thought that the essential absence of meta-torbernite and meta-zeunerite on the upper levels reflects the lack of sufficient concentration of copper and arsenic in the groundwater to precipitate these minerals until the solutions have seeped downward and leached several tens of feet of the vein. The abundance of "gummite" and uranophane on the upper levels, apparently derived from concentrations of pitchblende, demonstrates the availability of uranium to the solutions near the surface. Studies of the microcrystalline

vein quartz show the presence of small amounts of copper in inclusions of chalcopyrite, and copper and arsenic in tetrahedrite. The sparsity of these metals in the veins and their inaccessibility in fine inclusions tightly bound in the microcrystalline quartz would suggest little availability to the near-surface solutions. Thus the uranium which was not precipitated in "gummite" or uranophane near the original pitchblende source was carried into the altered wall rock, where much of it crystallized with calcium in meta-autunite, or at somewhat lower levels, with calcium and barium as meta-uranocircite. The absence of meta-uranocircite near the surface, and its presence on the lower levels in greater abundance than meta-autunite, may have a similar explanation in the low concentration of barium (leached from the barite of the veins) in solutions near the surface, and increasing concentration with depth.

Meta-torbernite was observed near the surface in only a few places, all of them in or near veins, where the concentration of copper relative to calcium may have been important locally. The greater abundance of copper-bearing uranium minerals in the lower levels is explained by the increased concentration of copper accumulated by leaching of the 90–125 feet of vein material. On the lower levels the uranium concentration may be too low (due to the lack of significant pitchblende concentrations below the upper levels) for any secondary mineral deposition in the wall rock, except near the vein and major fractures.

The problem of supergene enrichment versus depletion by groundwater activity has not been positively solved. There is a greater quantity of secondary minerals in the upper levels than can be related to known sites of primary pitchblende, since only meager traces of pitchblende remain. It is possible that uranium-rich solutions carried the metal down from a source above the present land surface, and deposited it in the favorable brecciated zones along the vein. The near-surface accumulations may have undergone continual solution and redeposition, moving downward with the gradually lowering land surface. However, the evidence that most of the uranium leached from primary ore has been redeposited as "gummite" only short distances from the pitchblende, together with the observation of remnant nodules of pitchblende and pseudomorphous outlines of pitchblende preserved by secondaries, and the reports of sizeable pitchblende pods having been mined out of the surface trenches, indicates that the primary uranium mineralization may have been sufficiently concentrated to explain the present concentration of secondary minerals without enrichment. The authors believe it is unlikely that appreciable supergene enrichment of the ore has taken place.

The possibility of a pitchblende enrichment by reduction of the U^{6+} ion at the water table is not considered a likely one due to the sparse distribution of sulfides in the siliceous veins and the apparent lack of other strongly reducing conditions.

ACKNOWLEDGMENTS

This study was done under Contract No. AT(30-1)-1390 with the U. S. Atomic Energy Commission. Mr. Ernest Thurlow, Mr. Leonard Jarrard,

and their staff provided guidance in the field, mine maps, and information on the local geology. Mr. Daniel Meschter, formerly of the U. S. Geological Survey, discussed some of the secondary problems with the authors and made available an unpublished manuscript (now TEIR 256 of the U. S. Geological Survey) on his study of the W. Wilson deposit. Messrs. Dewey Hinman and Buford Miles, together with Mr. Wade Lewis of the Elkhorn Mining Company, permitted access to the mine and donated a number of specimens.

Reference specimens were provided through the courtesy of Dr. George Switzer of the U. S. National Museum, and standard x-ray spindles were loaned by the U. S. Geological Survey's Trace Elements Laboratory. Dr. Clifford Frondel of Harvard University kindly authorized the reading of pertinent parts of his manuscript on the secondary uranium minerals. Appreciation is expressed to Mrs. Edith Emerson, Mrs. Jane Thornton, and Messrs. David Fenstermacher and Herbert Wilson, who aided in the laboratory investigations.

APPENDIX I

Section 1 (Fig. 6) in the north trench crosses a "gummite"-filled fracture in an ore zone. The "gummite" is confined to the fracture but uranophane extends from six to ten inches out into the wall rock. Meta-autunite is absent from the fracture zone, even though open spaces are available for deposition, and appears in moderate amounts about six inches from the fracture.

Section 2 (Fig. 6) in the east drift of the 30-foot sub-level crosses two veins and a fractured vein zone. Both meta-autunite and meta-uranocircite are more abundant beside the veins than within them. The bulk of the secondary mineralization is north of the central vein.

Section 3 (Fig. 7), which is in the central part of the 30-foot sub-level, also crosses two veins and a fractured vein zone. Meta-autunite and meta-uranocircite again are outside the vein, as is the small amount of phosphuranylite. "Gummite" is found in the northern vein zone, but is more abundant in pods between that zone and the central vein. It appears again below the moderately dipping south vein.

Section 4 (Fig. 8), the vertical section, shows considerable variation in the secondary content of the samples. There was no way to measure the distance of the samples from vein material which had been removed, but an estimated distance determined by the alteration of the wall rock is indicated in the figure. In this and several of the following sections, the field radioactivity measurements will be plotted with the laboratory values for comparison. It should be noted that the background count in the mine is variable and often quite high. The field value plotted is the total activity and includes this background. The main features of the section are the lack of meta-autunite, meta-uranocircite and "gummite" in the lower portions and the appearance of substantial amounts of meta-zeunerite below the 70-foot sub-level. The radioactivity and amounts of secondaries drop off below the 70-foot sub-level in spite of the fact that the samples are close to the vein.

Section 5 (Fig. 9) is at the eastern edge of an 18 foot raise and actually represents two sections, one horizontal, across a vein with silicified rock on either side; and the other vertical, across a subhorizontal limonite fracture near the horizontal section. As shown by the plotted radiometric counts the plate of rock above the fracture contains more radioactivity than the fracture or the wall rock below the fracture. This anomaly has been noted in several places in the mine.

Just south of the vein, uranophane and meta-uranocircite occur in moderate amounts above the fracture but are rare below it. Uranophane was the only mineral found in the limonite fracture. Meta-autunite occurs above the meta-

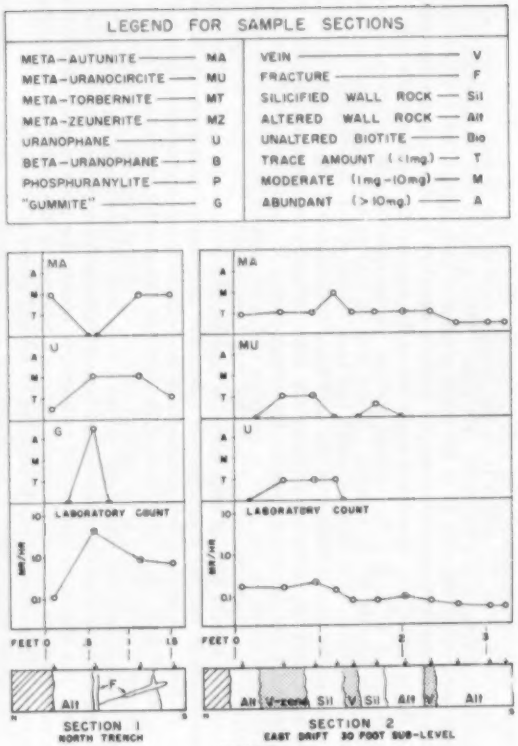


FIGURE 6

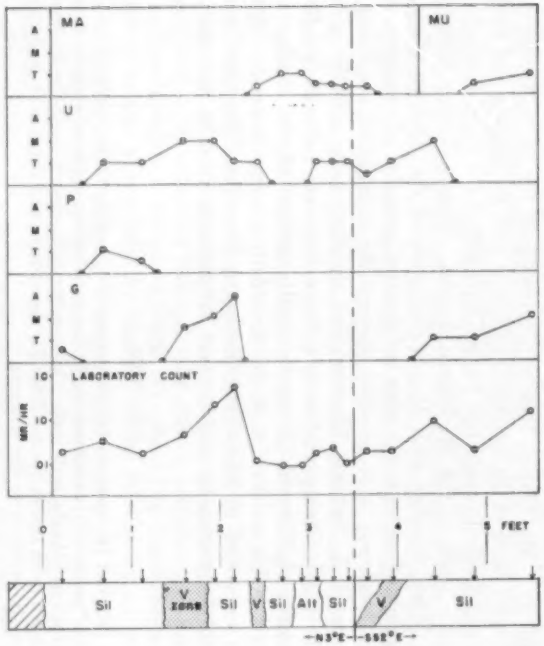


FIGURE 7

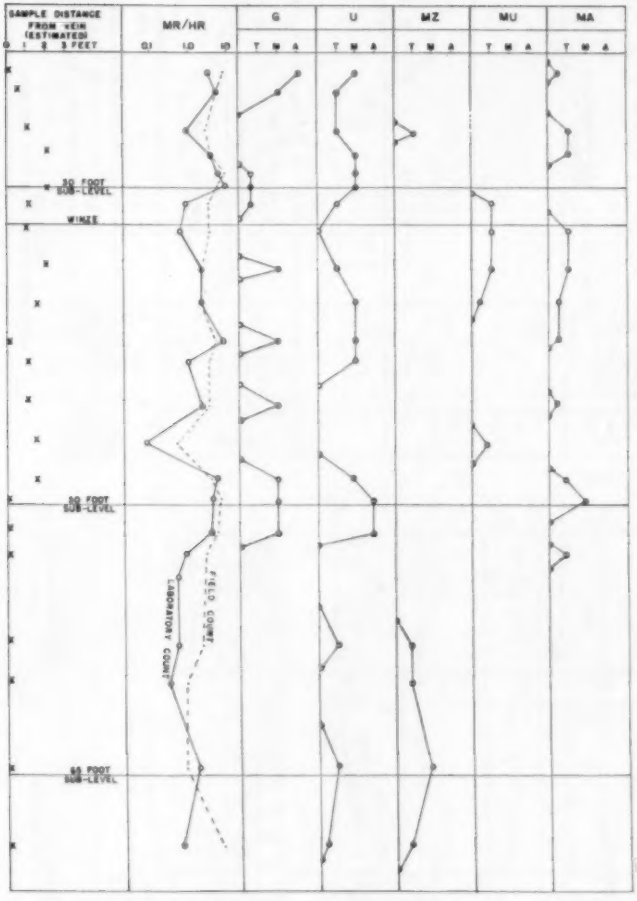

SAMPLE DISTANCE FROM VEIN (ESTIMATED)
0 1 2 3 FEET
MR/HR
G
U
MZ
MU
MA
T W A
50 FOOT SUB-LEVEL
WINZE
90 FOOT SUB-LEVEL
LABORATORY COUNT
FIELD COUNT
68 FOOT SUB-LEVEL
VERTICAL SCALE (feet)
0 2 4 8 12
SECTION 4
SAMPLES TAKEN FROM SOUTH WALL

FIGURE 8

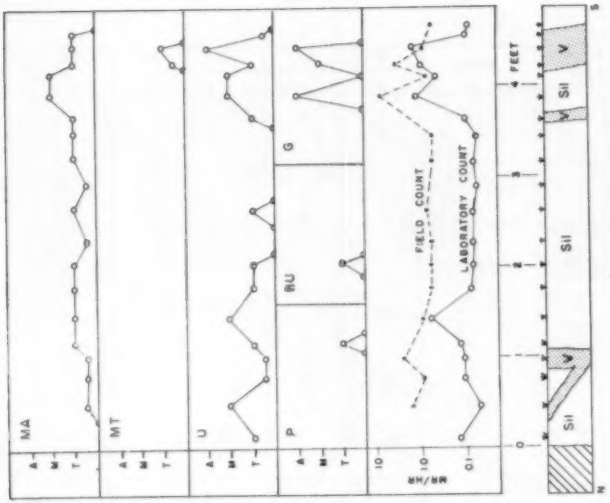


FIGURE 10

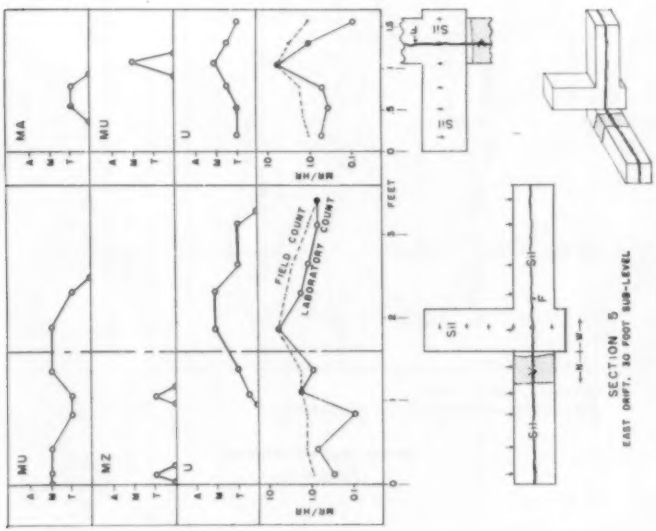


FIGURE 9

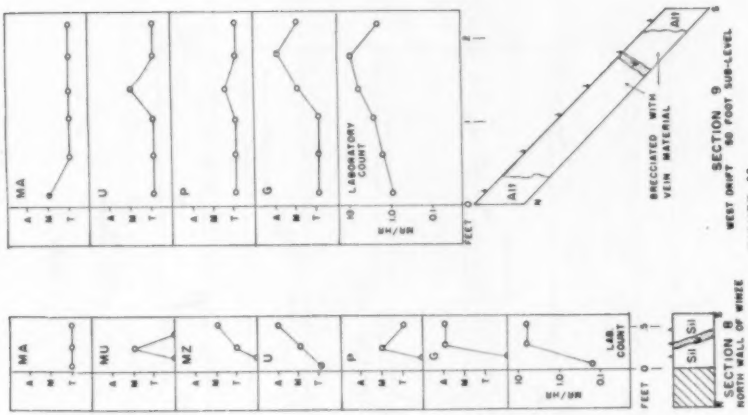


FIGURE 12

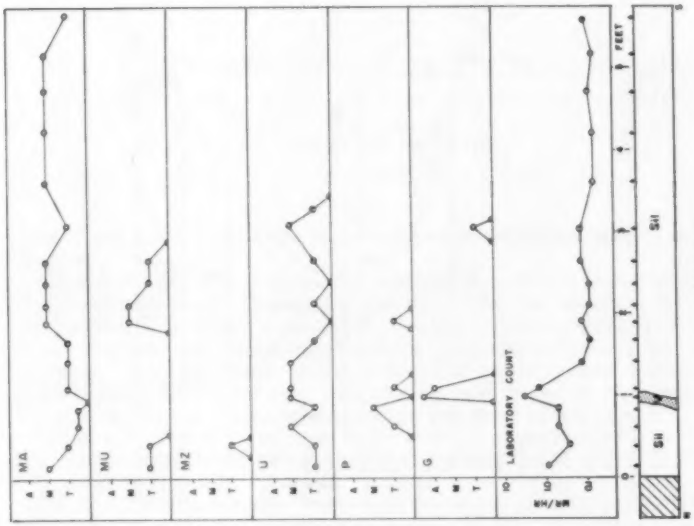
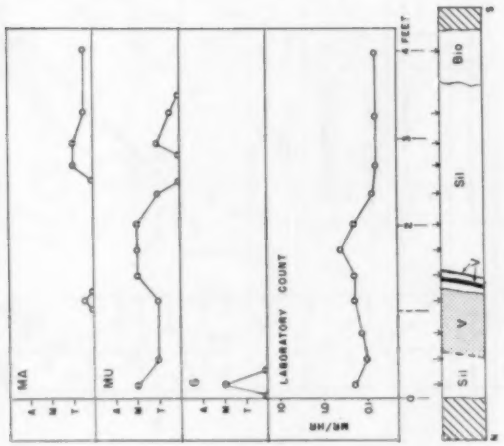
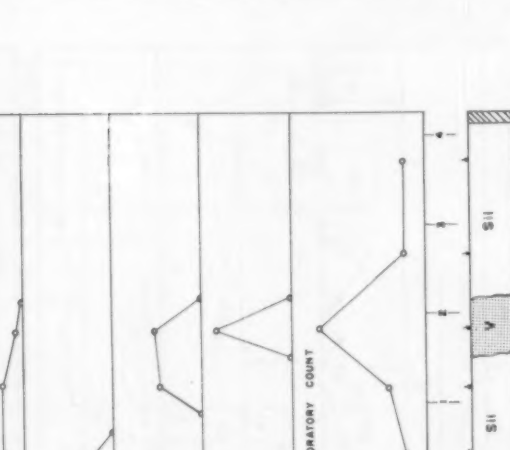


FIGURE 11



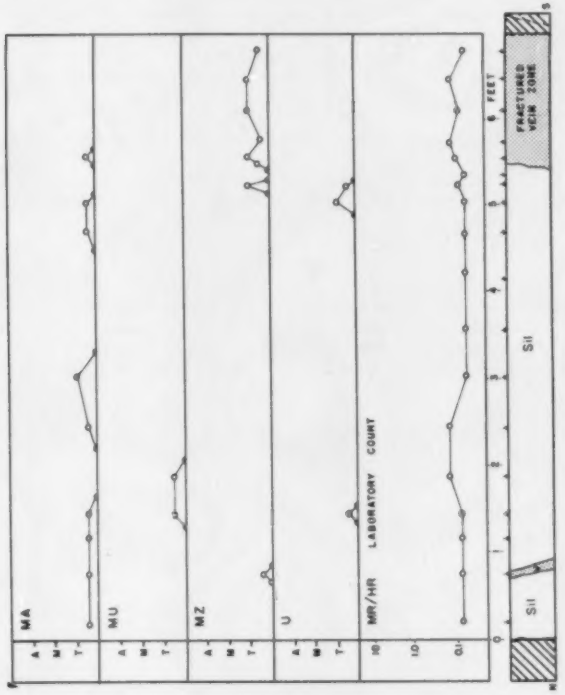
SECTION 10
EAST DRIFT OF 60 FOOT SUB-LEVEL

FIGURE 13



SECTION 11
65 FOOT SUB-LEVEL

FIGURE 14



SECTION 12
EAST DRIFT, 65 FOOT SUB-LEVEL

FIGURE 15

uranocircite and is rare in the horizontal section which was taken just above the fracture.

Section 6 (Fig. 10) is across the west end of a shallow winze in the floor of the 30 foot sub-level. Uranophane and "gummite" are abundant in and beside the southern vein, which is moderately fractured. Meta-torbernite is found only in the southern vein, and meta-autunite is most abundant near, but not in, the "gummite" pods just north of this vein. The nearly vertical northern vein is smaller, shows little fracturing, and contains only traces of secondary minerals. Phosphuranylite and beta-uranophane occur just south of this vein.

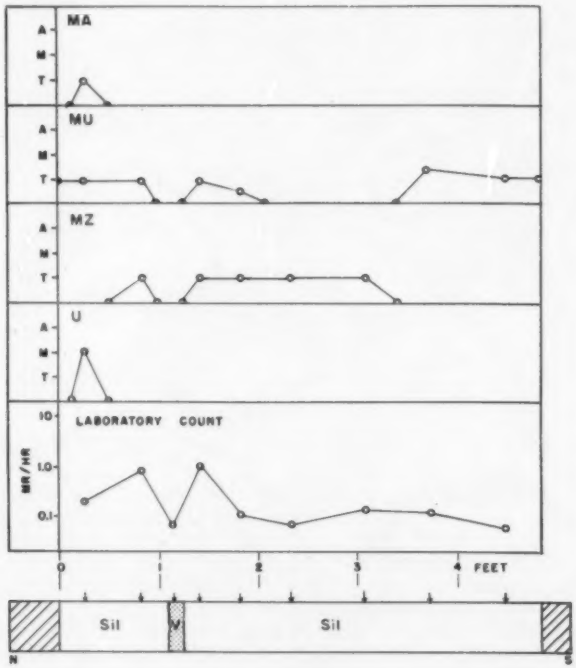
Section 7 (Fig. 11) was taken at the east end of the shallow winze on the 30-foot sub-level. Only one vein occurs and over four feet of wall rock south of the vein could be sampled. "Gummite" is found in as well as beside the small, fractured vein but meta-autunite, meta-uranocircite and phosphuranylite which occur on either side of the vein are absent in the vein itself. Uranophane is as abundant within the vein as beside it and is present up to three and one-half feet from the vein. Meta-autunite continues in moderate amounts to the edge of the section

while the other secondaries can be traced only two and one-half feet away from the vein.

Section 8 (Fig. 12). This set of three samples from an offset in the north wall of the winze on the 30-foot sub-level shows a concentration of meta-uranocircite and phosphuranylite in the thin vein. Meta-zeunerite, uranophane and "gummite" are most abundant just south of the vein. The only secondaries adjacent to the vein on the north side are meta-autunite and meta-uranophane, both present in trace amounts.

Section 9 (Fig. 12) is at the west end of the 50-foot sub-level and was cut at a 45° angle down across the face through a wide brecciated vein zone. Meta-autunite is in moderate amounts north of the vein and decreases in amount in the vein zone The other minerals, uranophane and phosphuranylite, except for one sample, are also present in trace amounts in the vein zone. "Gummite" is concentrated in the southern part of the vein zone.

Section 10 (Fig. 13), at the east end of the 50-foot sub-level, shows the major part of the "gummite" and uranophane to be in or just north of the vein. Meta-uranocircite is rare and does not occur in the vein. Meta-autunite is consistently present in trace amounts in the vein and one wall, but absent in the other.



SECTION 13
EAST DRIFT 90 FOOT SUB-LEVEL

FIGURE 18

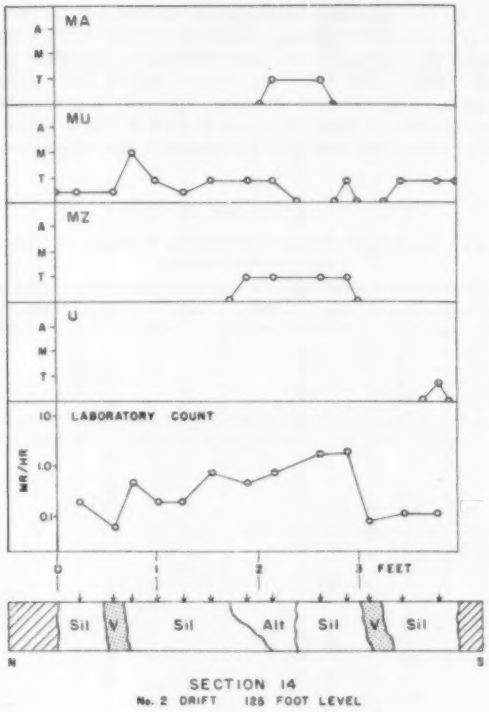


FIGURE 17

Section 11 (Fig. 14) was cut across the back of the middle section of the 70-foot sub-level. One major vein was crossed and the sampling continued into wall rock in which some fresh biotite remained. The only "gummite" occurs with a concentration of meta-uranocircite just south of the vein. A trace amount of meta-autunite was noted in an unusual occurrence in the fractures of the vein. Most of the meta-autunite and meta-uranocircite occurs south of the vein and traces of meta-autunite were noted as far out as the slightly altered, biotite-bearing wall rock.

Section 12 (Fig. 15) was taken near the eastern end of the 70-foot sub-level and contains only trace amounts of secondary minerals. Meta-zeunerite developed in both veins while uranophane formed just outside the veins. Meta-autunite occurs in the southern vein zone only in the fringe, but extends from here across the section into the northern wall.

Section 13 (Fig. 16) is in the 95-foot sub-level and crosses a vein devoid of secondaries. Meta-autunite and uranophane occur in only one sample, on the south side of the vein. Meta-uranocircite and meta-zeunerite are fairly widely distributed on both sides of the vein, but only in trace amounts.

Section 14 (Fig. 17) was taken from the No. 2 drift on the 120-foot level. Because of the steep slope of the ground, this drift is only 30 feet below the surface and for this reason the exposures are more directly comparable with those on the 30 foot sub-level. Both veins show the typical lack of secondaries and the bulk of their deposition has been between the veins, with minor concentrations near each one. Meta-uranocircite was found in traces in most of the samples. Meta-autunite and meta-zeunerite were restricted to a few samples, and uranophane was observed in only one.

APPENDIX II

AMOUNTS OF SECONDARY URANIUM MINERALS PRESENT IN EACH SAMPLE AND SAMPLE SECTION

Sample number	MA	MU	MT	MZ	U	BU	P	G
North trench								
418	T				A			AA
416	T				M			AA
Section 1	M				M			AA
South trench								
479	TT				M			A
478	T				A			A
481	T				M			M
477	TT				A			AA
30-foot sub-level								
452	TT		M	M				
451		M			T			
449					M			M
447	T							A
480	A	A		A	M			
479	TT				M			A
Section 3	T	T			M		T	A
7224	TT							A
7225		M						A
9432					M			
Section 4	T			T	M			A
450	M	T			M			A
Section 2	M	T			T			
Section 5	T	M		T	M			
Winze								
Section 6	M		T		A	T	T	A
Section 8	T	M		M	A		M	A
Section 7	M	M		T	M		M	AA
Section 4	T	T			T			
50-foot sub-level								
Section 9	T	T			M		T	A
419	T							T
440					M			A
453					TT			
420	T				T			T
441					M			A
7220	A	A			A			
Section 4	M	T			A			A
448	T	T					T	
Section 10	T	T			M			AA

APPENDIX II—*Continued*

Sample number	MA	MU	MT	MZ	U	BU	P	G
70-foot sub-level								
439	M	M						
438		T						
Section 11	T	M						M
Section 4	T			M	A			M
437				T	TT			
Section 12	T	TT		T	T			
421	T		T	M				
425			M		A			A
424				M	T			
423				M				
422			T	A				
95-foot sub-level								
436				A	T			T
Section 13	T	T		T	M			
457				T				
427				M			T	
426				M				
120-foot level								
2636				TT				
2654				TT				
2762			M					
2682		T		M	M			
2692				TT				
2764			M					
242		TT						
244		TT			TT			
2662			T					
2612				T				
216				TT				
2603				T				
No. 2 adit								
Section 14	T	M		T	TT			

PENNSYLVANIA STATE UNIVERSITY,
UNIVERSITY PARK, PENNA.,
Aug. 8, 1956

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COBALT–ARSENIC MINERALS ASSOCIATED WITH APLITES, AT COBALT, ONTARIO

EDWARD SAMPSON AND M. E. HRISKEVICH

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ABSTRACT

In the Bass Lake area, about 3 miles from the town of Cobalt, soda-rich aplites are developed in the upper part of the Nipissing diabase sheet. Associated with these aplites are the following metallic minerals: pyrite, skutterudite, glaucodot, gersdorfite, rammelsbergite, chalcopyrite, tenantite, niccolite, bismuthenite. The aplites, with the associated metallic minerals, are thought to be late-stage differentiates from the tholeiitic magma from which the diabase was formed and indicate that such a magma may yield minerals carrying Co, As, S, Ni, Ag, and Bi. The major mineralization of the Cobalt region is ascribed to a similar magma in depth.

INTRODUCTION

THIS paper describes a minor feature of cobalt mineralization in the Cobalt, Ontario district that the writers believe has a bearing on the larger problem

of the genesis of the major cobalt-silver bearing veins of the camp, and on the general problem of the genesis of an ore-forming solution carrying Co, As, S, Ni, Cu, Ag, and Bi in close genetic relation to aplites, which in turn, are formed by the differentiation of a tholeiitic magma.

Most of the field work on which this paper is based was done by Hriskevich during the field seasons of 1950 and 1951 and was part of a regional mapping

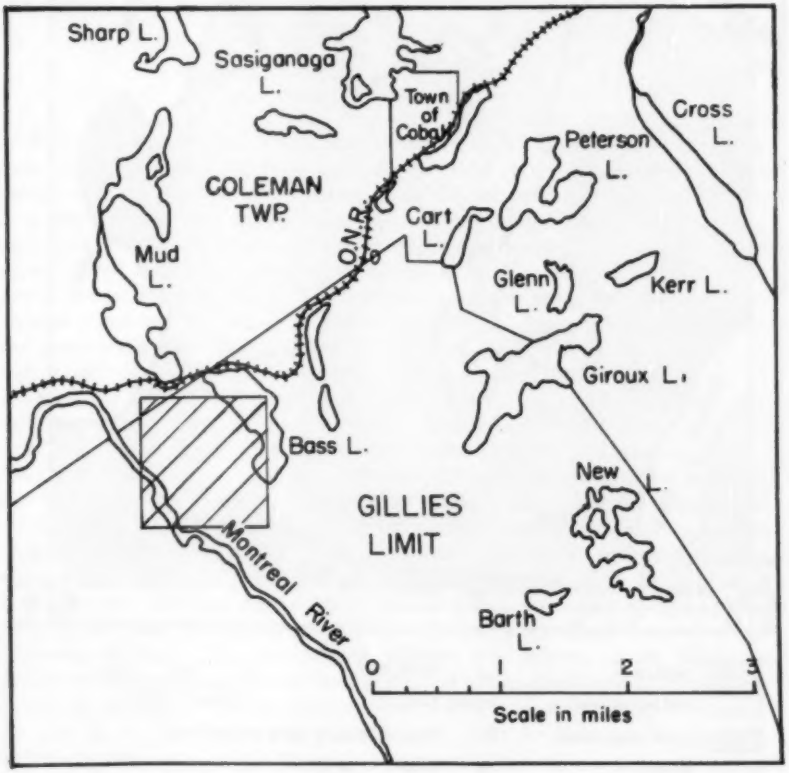


FIG. 1. Index map of Cobalt district, showing area of detailed study.

project (Fig. 1) undertaken by the Ontario Department of Mines under the direction of Dr. Robert Thompson. The area covered by the detailed map (Fig. 2) is about one square mile, the center of which is about 3 miles S 35° W from the town of Cobalt. This area contains the aplite dikes that are the subject of this paper. In addition to the areal mapping, Hriskevich systematically collected samples from three mine shafts that penetrate deeply into the diabase sill. The material, from the shaft sections together with

samples collected on critical traverses of the diabase exposed on the surface, served as the basis for a study of the differentiation in the diabase sill, which was presented as a doctors thesis (3) at Princeton University. This study gave the background for the study of the aplites. During the field study a few specimens had been taken of the metallic minerals from some of the prospects

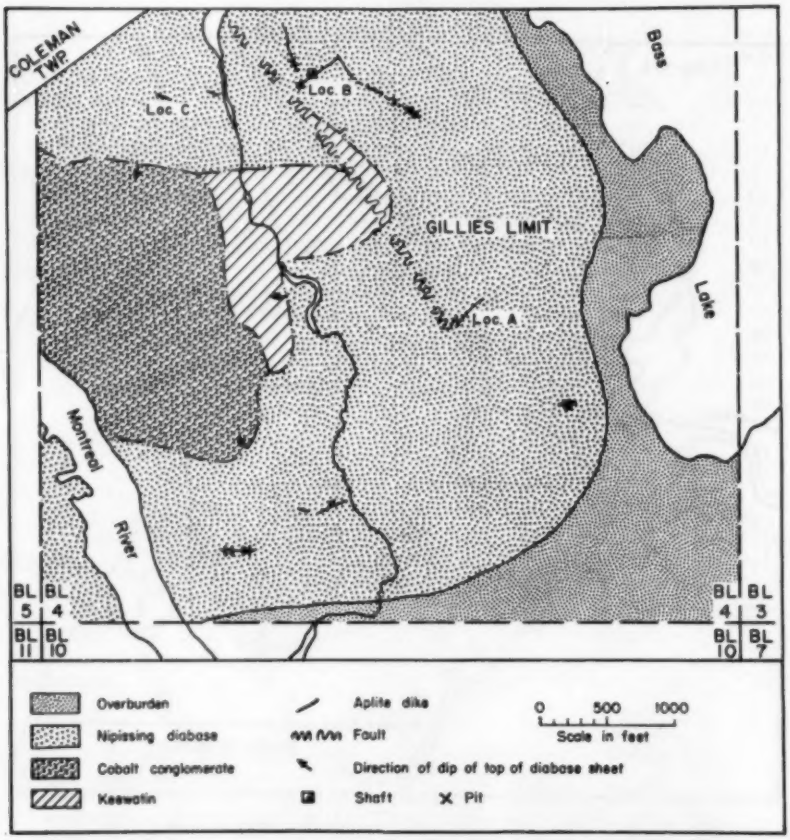


FIG. 2. Geologic map of Bass Lake area showing location aplites.

where mineralization is clearly related to aplites. A microscopic study of these minerals by both writers indicated the desirability of collecting additional material for study and a further field examination. The writers made a short trip to Cobalt in May 1952 and obtained most of the material on which this paper is based.

Acknowledgments.—All students of the geology of the Cobalt region are

under the greatest debt to Dr. Robert Thomson of the Ontario Department of Mines. For some years the Department has been conducting a study of the region with detailed remapping of a large area under the direction of Dr. Thomson. The field mapping of Hriskevich was but a small part of this large program. The writers had the benefit of stimulating discussion with Dr. Thomson and are greatly indebted to him. A grant from the Department of Geology of Princeton University covered the expenses of the detailed study of the aplites on which the present paper is based.

NIPISSING DIABASE

Structural Relations

The Nipissing diabase of the Cobalt area has the form of an undulating sheet of rather constant thickness. Shafts have been driven through the diabase at four localities and in each place the thickness is about 1,100 feet. In a general sense the diabase was intruded along the contact of flat-lying sediments of the Cobalt series and the underlying Keewatin which consists of volcanics and sediments, closely folded, and in nearly vertical position. The Cobalt series was laid down on a surface of substantial relief amounting to perhaps three to four hundred feet. Post-Cobalt and pre-diabase deformation produced gentle folding in the Cobalt series, which in places has dips as high as 20°–30°. Where the Cobalt series lies in basins the diabase may be underlain by Cobalt sediments, and, where the Cobalt series is structurally high, the sheet is overlain by Keewatin. However in much of the area the sheet is intruded directly on the unconformity. Minor cross-cutting by the sheet with high dips is common. Post-diabase faulting, up to a few hundred feet, took place, but there has been no substantial folding since the intrusion of the diabase. This structural stability is of importance in considering certain features of the differentiation of the sheet and particularly in considering the origin of ore-forming solutions that formed the rich silver-cobalt bearing veins of the region. A large region about Cobalt shows no period of igneous activity, other than the intrusion of a few olivine basalt dikes, later than the Nipissing diabase. The ore-forming solution was related to the Nipissing diabase or its parent magma and was generated under conditions of remarkable structural stability. This is in strong contrast to most mining districts where the genesis of the ore-forming solution took place in close association with major orogeny.

Summary of Petrology

A detailed petrographic and chemical study of the diabase sheet reveals that the original magma was of the thoeiilitic type and that it has been clearly differentiated. The upper and lower margins are composed of undifferentiated quartz diabase. Olivine-bearing hypersthene diabase occurs as saucer-like masses in the lower part of the sheet and these are confined to original structural basins. In the central part of such structural areas in the olivine-bearing hypersthene diabase makes up a major portion of the section. In the intervening arched areas it is not present and there the major lower part of the

sheet, above the undifferentiated quartz diabase, consists of quartz-bearing hypersthene diabase. This is overlain by a quartz-bearing diabase, which shows extreme variation in texture from medium to very coarse and is known locally as "varied texture" diabase. The upper portions of the arched areas are nowhere preserved, but in all probability consisted in large part of granophyric materials that were concentrated there during the differentiation of the sheet.

MINERALIZED APLITES IN THE AREA WEST OF BASS LAKE

Manner of Occurrence

The location of the mineralized aplites described in this paper is given in Figure 2.

The aplites occur as narrow dikes in the upper part of the diabase sheet. The more important set of dikes has a general east to northeast strike, and a less important set has a north to northwest strike. Dips in all cases are steep. Information as to the length of the dikes is meagre because of the extensive cover of glacial drift. In localities where prospecting has been done, mineralized aplite has been traced for as much as 400 feet. The width of the dikes ranges from less than an inch to a maximum of about a foot and a half. Widths within a single dike may vary from a foot to an inch in only a few tens of feet. Detailed geologic mapping of the Bass Lake area has revealed that the aplites are confined exclusively to the diabase, and, more particularly, to the upper portion of the sheet. Mineralized aplites have not been found by mapping or prospecting in either the Keewatin rocks or the sediments of the Cobalt Series in the Bass Lake area.

However, a "granite" (aplite) dike occurs at the University Mine on the north shore of Geroux Lake. The dike is about 40 feet wide, strikes about east-west, and is intrusive into the diabase sheet and the Cobalt series sediments immediately below the sheet. Its position near the base of the sheet may be a direct consequence of the presence of the Kerr Lake arch, which is an original feature of the sheet, since during the later stages of differentiation of the diabase magma, the arch (now eroded) may have served as a locus of collection for the more acidic fraction. It seems reasonable to assume that upon partial solidification of the diabase, the still fluid aplite may have intruded downward probably into a fissure, to form the large aplite dike.

The contact relations of the aplite and diabase are extremely variable. At some places the contact is very sharply defined. The importance of well-defined contacts of aplite and diabase in establishing the intrusive nature of the aplite is discussed at more length in the section dealing with the origin of the aplites. At other places a gradation occurs from aplite, through aplitized diabase, to unaltered diabase, the zone of gradation being as much as about 6 inches wide. At one locality sharp angular fragments of what were originally diabase are included in the aplite. Alteration of these fragments is generally intense but the original diabasic texture is still preserved. Where the inclusions were subjected to more intense alteration by the enclosing aplite, the inclusions are rounded and the boundaries are markedly less well defined.

Petrographic Description

The unmineralized aplite consists essentially of albite and quartz. The accessory minerals include apatite, sphene, opaque iron oxide, and probably zircon. Chlorite is present in varying amounts as a secondary mineral. The proportion of quartz in the aplites is variable, being as high as 30 percent in some and almost lacking in others. Albite has a euhedral to subhedral habit and is characterized by numerous submicroscopic inclusions of reddish hematitic material. Feldspar with plaid twinning characteristic of microcline occurs in variable, although minor, amounts. The optical sign is positive, and indicates that the feldspar is albite. Chemical data reveals the presence of only very small amounts of K_2O in the aplites. Partial analyses of an aplite dike and a micropegmatite vein within the dike were made in the course of Hriskevich's study of the petrology of the diabase as follow:

	1	2
Na_2O	5.51	4.93
K_2O	0.22	0.20

1. Aplite dike, 1¾ inches wide. Concession 8, Lot 6, Lorrain Township.
2. Micropegmatite vein, ½ inch wide from within aplite dike of 1. Concession 8, Lot 6, Lorrain Township.

Eileen H. Oslund, Analyst.

A review of the literature shows that all available superior analyses of aplite in the Cobalt and Gowganda areas show similar low content of K_2O.

Metalization

General.—Metallic minerals occur, in two ways in the aplites. The most common manner of occurrence is in the form of irregular replacement veins (Fig. 3). Associated with these veins are grains of metallic minerals disseminated through the aplite. The veins and disseminations contain the elements Fe, Co, As, and S. The other, less common, form of occurrence of metallic minerals is in association with quartz and calcite that fill vugs within the aplite (Figs. 4, 5). This assemblage of minerals carries the elements listed above and, in addition, Cu, Ag, and Bi. The mineralogy of the two types of occurrence is described below.

Veins and Disseminations.—The veins in the aplite are extremely irregular and are unrelated to clear fractures. Vein boundaries are ill defined and, for the most part are gradational and clearly formed by replacement. Some veins consist almost entirely of metallic minerals, the only non-metallic being a small amount of calcite, which is also disseminated in the adjacent aplite. In other veins calcite may form a substantial portion of the introduced material.

The metallic minerals from localities A and B are listed in Figure 6.

Vug Filling.—An unusual but particularly significant feature of some aplites is the occurrence of filled vugs that indicate clearly a genetic sequence starting with the last stage of crystalization of the aplite. The mineral succession is: albite, quartz, carbonate and metallic minerals. This is remarkably well shown at Locality C of Figure 2. Figures 4 and 5 show a cross section

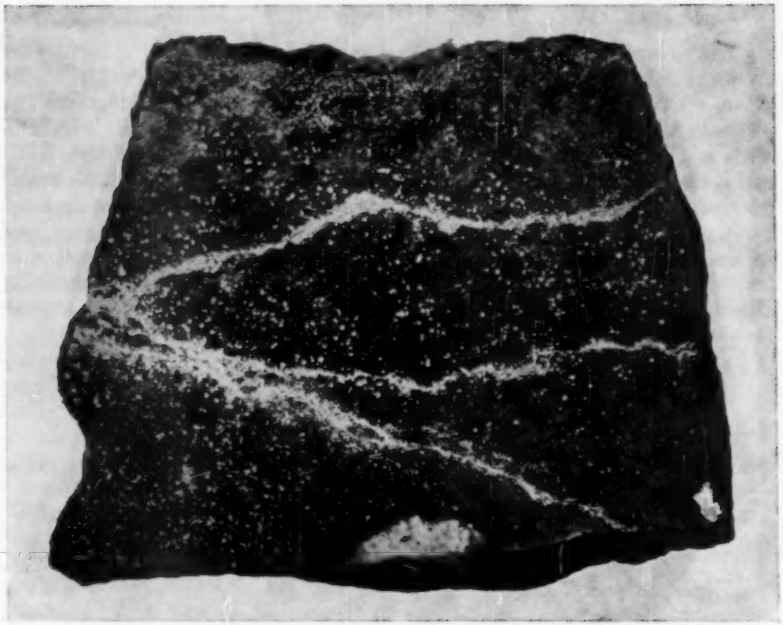


FIG. 3. Replacement veins in aplite. From locality B of Figure 2. Mag. 0.86.

of such a filled vug. This specimen, from the largest vug noted, came from the central portion of an aplite dike about one foot wide. The dimensions of the vug are 1½ by 7 inches by over a foot long. The walls of the original vug are coated with pink albite crystals, with idiomorphic faces toward the center of the vug. The average size of the crystals is about a quarter of an inch,

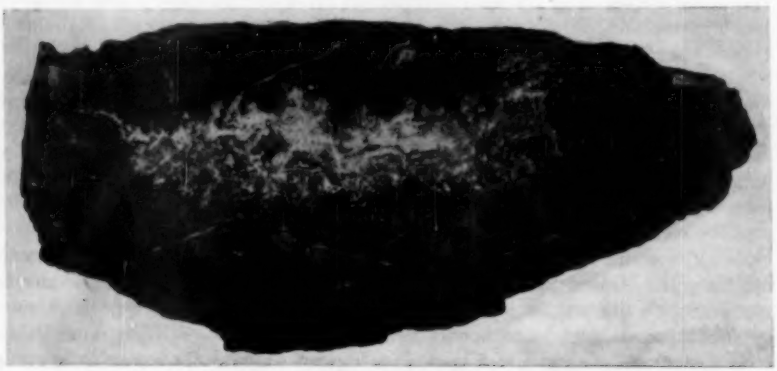


FIG. 4. Filled vug in aplite. From locality C of Figure 2. Mag. 0.46.

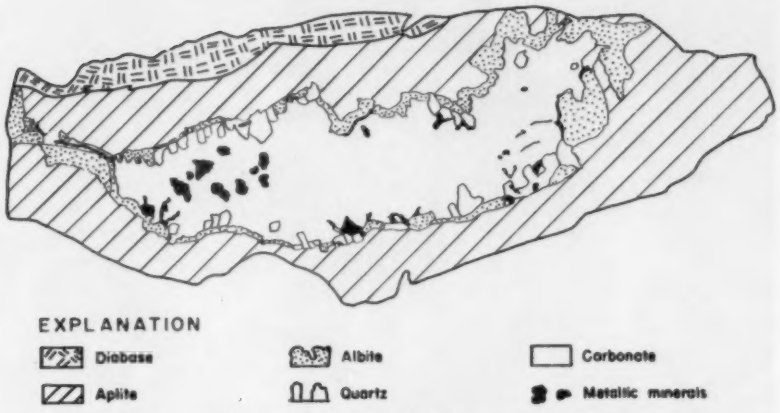


FIG. 5. Tracing of face illustrated in Figure 3. Mag. 0.48.

which is much coarser than the albite of the aplite. The albite crystals are coated by well-formed prismatic crystals of quartz. The central part of the vug is filled with calcite. The calcite-forming solution has corroded the quartz strongly and in the section illustrated few clearly defined quartz crystals are left. The metallic minerals occur in part as irregular blebs in the carbonate and in part as irregular veinlets within the carbonate. Minute veinlets of calcite, carrying a small amount of metallic minerals, cut the border of the vug and extend out for a short distance into the aplite.

The metallic minerals present are listed under Locality C of Figure 6.

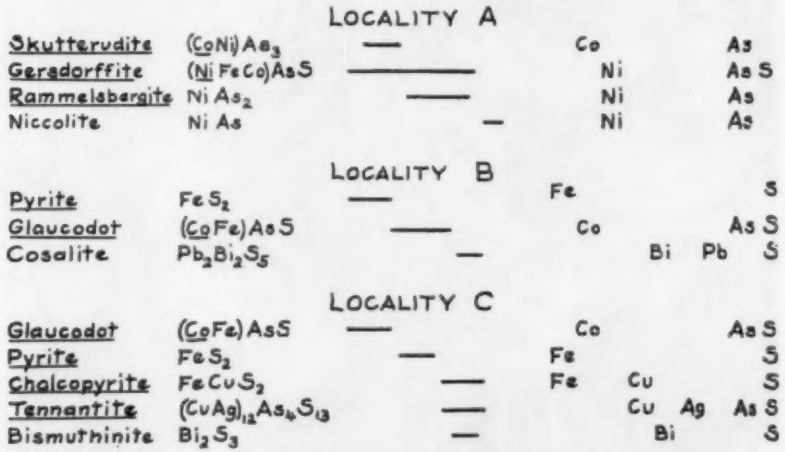
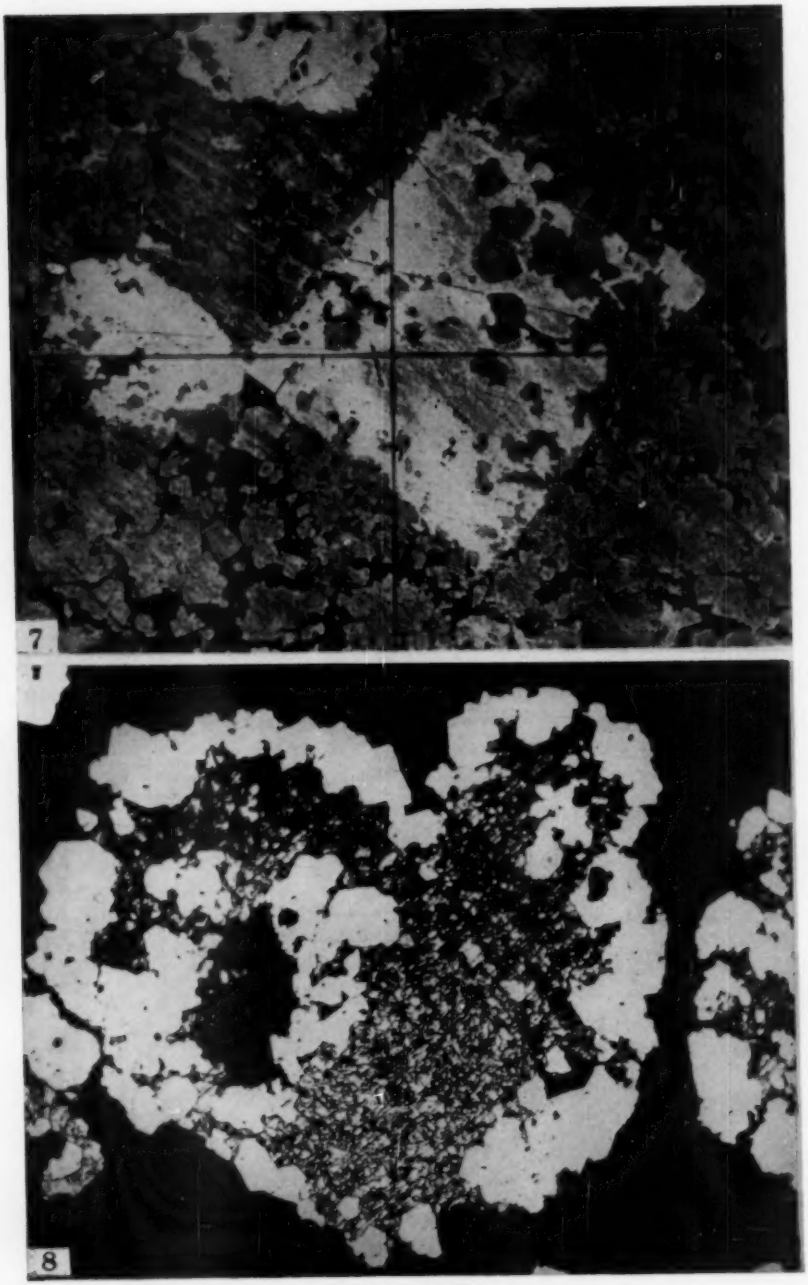

LOCALITY A
Skutterudite (CoNi)As3 Co As
Gersdorffite (NiFeCo)AsS Ni As S
Rammelsbergite NiAs2 Ni As
Niccolite NiAs Ni As
LOCALITY B
Pyrite FeS2 Fe S
Glaucodot (CoFe)AsS Co As S
Cosalite Pb2Bi2S5 Bi Pb S
LOCALITY C
Glaucodot (CoFe)AsS Co As S
Pyrite FeS2 Fe S
Chalcopyrite FeCuS2 Fe Cu S
Tennantite (CuAg)12As4S13 Cu Ag As S
Bismuthinite Bi2S3 Bi S

FIG. 6. Time relations of minerals and elements.



FIGS. 7-8

Mineral Descriptions

Figure 6 lists the metallic minerals recognized and their time relations. All minerals except pyrite, chalcopyrite, and niccolite have been determined by X-ray powder diffraction using a standard small size camera. For this the writers are greatly indebted to Mr. L. C. Coleman, who took the photographs and made the computations, and to Professor L. G. Berry who made available the catalogue of X-ray diffraction data of Queens University.

Skutterudite.—This mineral is an abundant constituent at locality A where it occurs as relatively large well-formed crystals. It contains included gersdorffite. At this locality the concentration of iron and sulfur seem to be the lowest and this seems to have favored the occurrence of skutterudite rather than glaucodot.

Gersdorffite.—Gersdorffite is the predominant nickel-bearing mineral at locality A, where it has a rather peculiar distribution as is shown in Figure 7. Here the skutterudite contains a few grains of gersdorffite that have the same habit as the much more abundant, and more closely packed, grains outside of the skutterudite crystals. This distribution is interpreted as indicating that some gersdorffite is contemporaneous with skutterudite but that most of the gersdorffite is later than skutterudite. Gesdorffite also is found with rammelsbergite in clot-like masses in which pure rammelsbergite forms the central part of the mass with a border of gersdorffite. These relations are shown in Figure 8.

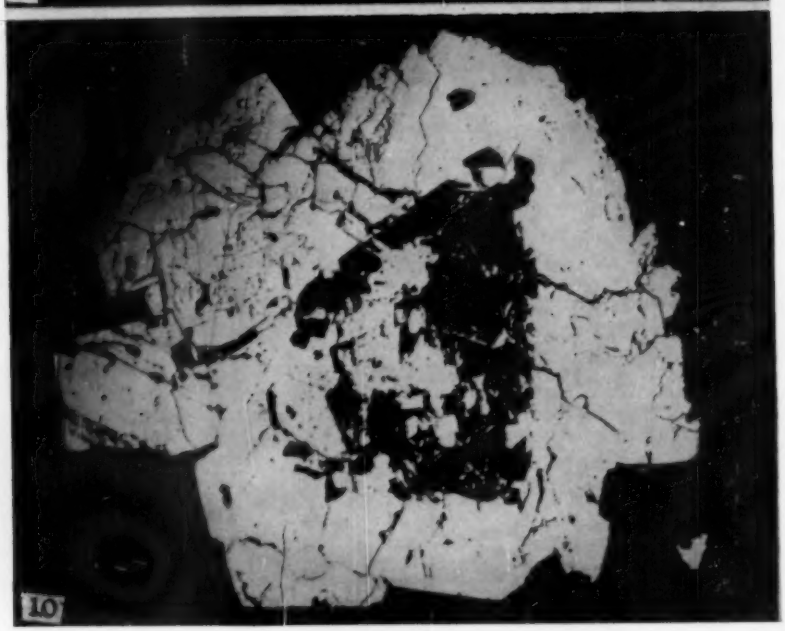
Rammelsbergite.—Rammelsbergite is an abundant mineral at Locality A. It has been discussed under gersdorffite, with which it is associated.

Niccolite.—Niccolite is found in the specimens from locality A only. In these specimens it is present in only a very minor amount. It is molded on gersdorffite and appears to have been the last metallic mineral to have crystallized.

Pyrite.—Pyrite is lacking at locality A where the mineral assemblage indicates a deficiency of iron and a small concentration of sulfur as compared to localities B and C. At locality B pyrite is common and was clearly the first metallic mineral to form. Pyrite is commonly coated with a crust of glaucodot crystals as is shown in Figure 9. A peculiar feature of these pyrite cores is that they have been replaced, in some cases almost completely, by quartz and calcite, leaving the outer rim of gersdorffite unaffected. This process is shown in Figure 9, and 10. In Figure 9 the replacing minerals have formed a shell separating the two metallics and in Figure 10 the process has gone to the stage where the pyrite is almost gone. Note that in Figure 10 a blue filter has not been used and pyrite and glaucodot are not distinguishable. The outer boundary of the pyrite is indicated by the projection of the outer straight boundaries of quartz.

FIG. 7. Skutterudite (large crystals) included in and enclosing gersdorffiite (large light-colored crystals). Skutterudite, etched by $KMnO_4$, darker than gersdorffite and lighter than gaugue. Mag. 160.

FIG. 8. Rammelsburgite (etched by HNO_3) surrounded by gersdorffite. Mag. 180.



FIGS. 9–10

At locality C pyrite is found only with chalcopyrite, which is clearly later than glaucodot. At this locality, where filled vugs are so remarkably shown, chalcopyrite and associated minerals occupy the central part of the filling with the glaucodot largely coating the quartz of the walls. The pyrite is intensely replaced by chalcopyrite.

Glaucodot.—At locality B and C nickel is essentially absent and iron is abundant. Glaucodot is the only cobalt-nickel arsenide-sulfide and the X-ray studies indicate that it is the cobalt-rich variety, alloclasite.

FIG. 11. Cosalite (gray) etched with $FeCl_3$, moulded in glaucodot (white). From locality B. Mag. 179.

Chalcopyrite.—Chalcopyrite is a common mineral in the central parts of the filled vugs of locality C. It is intergrown, with mutual boundaries, with tennantite, and strongly replaces pyrite.

Tennantite.—The fahlerz is indicated as tennantite by microchemical tests. It is intergrown with chalcopyrite at locality C where it is common. The unit volume given by the X-ray, which is high (a 10.39) indicates a probable high silver content.

FIG. 9. Pyrite rimmed by glaucodot. Pyrite relatively dark color through use of dark blue filter. Mag. 215.

FIG. 10. Glaucodot molded on pyrite which has largely been replaced by calcite. Original boundary of pyrite is indicated by straight lines. Compare with Figure 9. Mag. 173.

Bismuthinite.—This mineral occurs as small grains within tetrahedrite in the filled vugs of locality C. Its identity is established by the X-ray and by etch tests.

Cosalite and unknown.—At locality B a small amount of soft, gray, anisotropic minerals occur interstitial to, and veining glaucodot (Fig. 11). It appears that two minerals are present although the principal one is cosalite. These minerals are clearly the latest to form.

Coleman took two minute samples from a polished section and made X-ray power photographs. These have been carefully studied by Sampson. In one the lines agree satisfactorily with those of cosalite. In the other the lines, as recognized by Coleman, are in fairly close agreement with pavonite ($Ag_2S \cdot 3BiS_3$) (5). X-ray fluorescence examination of the surface of the polished section indicates the presence of bismuth, lead, and small amount of silver in addition to cobalt, arsenic, and iron from the mineral gersdorffite of which the section is mainly composed. The major part of the soft mineral has etch tests exactly matching cosalite and not in good agreement with pavonite. In summary the soft material appears to be mostly cosalite and probably a small amount of another unknown mineral.

ORIGIN OF THE APLITES AND GENESIS OF ORE-BEARING SOLUTIONS

Conflicting Opinions on Genesis of Aplites.—Most previous investigators agree that the aplites associated with the diabase intrusives of the Cobalt and Gowganda areas are genetically related to the diabase, and are a product of differentiation of the diabase masses. Bastin (1), however, took exception to this view and ascribed the origin of aplites to alteration of the diabase along fractures by hydrothermal solutions which are not derived from the differentiation of the sill.

Field Data.—In the Cobalt and Gowganda areas, aplite dikes of the type described in this paper are exclusively confined to the diabase, and where the diabase intrusive has a sheet-like habit, to the upper half of the sheet. In the area west of Bass Lake, aplite dikes are not found in the rocks of the Keewatin and the Cobalt series, although in the diabase, eleven such dikes are known. Thus the distribution of aplites alone indicates a close relationship between aplite and diabase.

The contact relations of aplite and diabase indicate that the aplite was emplaced as a highly mobile and reactive magma rather than having formed by hydrothermal alteration of diabase along fractures. Sharply defined contacts between diabase and aplite are found in many localities, the presence of angular inclusions of diabase in aplites and the presence within certain aplites of vug-like masses in which comb structure is well shown all attest to the magmatic emplacement of aplites. The gradational contacts emphasized so strongly by Bastin as indicating a hydrothermal origin of the aplites, are readily explained if the magmatic origin is accepted. That the aplitic magma was rich in volatile constituents is clear from the occurrence of vug-like masses rich in carbonate, which occupy a medial position in the aplite. Even where the contact between diabase and aplite is sharp, the diabase has been intensely altered adjacent to the aplite.

Some occurrences of aplitic rock are known where the aplite has transitional boundaries against diabase. Such masses are generally of irregular outline and show little, if any, relation to planar fissures. In these instances the writers believe that the aplitic material was emplaced before the complete solidification of the diabase. Such masses are analagous to "pegmatitic" bodies commonly formed in diabases elsewhere.

One of the most detailed studies made of the late differentiates of a diabase magma was carried out by Shannon (6) on the diabase of Goose Creek, Virginia. This diabase, of Triassic age, is thoroughly characteristic of the diabase sheets that extend discontinuously from Virginia, across Pennsylvania and New Jersey and has much in common with the diabase of Cobalt. Shannon describes small, persistent, albite-rich aplite dikes, averaging about three cm. wide. These dikes have sharp contacts with the diabase. "They are usually, though not invariably accompanied by more or less alteration although this is not believed to have been due to the aplite as such but rather to the reopening of the fracture to permit the action of later solutions" (p. 27). Regarding the origin of the dikes Shannon writes: "The normal diabase grades into diabase pegmatite by gradual coarsening of grain but there seems to be a sharp break in composition between diabase pegmatite and the highly albitic rocks," albitic pegmatite and albite aplite. However Shannon considered that there was a close genetic relation between the pegmatites and the aplites.

Early workers in the Cobalt region observed the presence of aplite dikes and mineralization associated with them. In 1913, Miller (4) noted:

> Especially in the Elk Lake and Gowganda areas the Nipissing diabase is frequently cut by narrow dikes of aplite and granophyre. The material in these dikes is believed to represent residual, acidic segregations of the diabase magma . . . the aplite dikes associated with the Nipissing diabase are found to be characteristically high in soda and low in potash (p. 104).

Concerning the area of the Montreal River and Temagami Forest Reserve, he said in the same publication (p. 159)

> The silver and cobalt bearing deposits, all of which are found in the diabase, may be divided into two types, of which the first mentioned predominates, but has not proved to be of economic importance: (1) aplite dikes; (2) calcite veins. It would appear that there is no hard and fast line of division between the two types. . . . These aplite dikes are supposed to have been formed by cracks appearing in the diabase as it cooled and contracted; they were subsequently filled with vein or dike material, which probably came from hot solutions (aqueo-igneous) given off by parts of the diabase still molten. Small scales of native silver occur frequently in the aplites.

Burrows noted (2) that at Gowganda:

> A number of the veins are aplitic in composition. The aplite is considered a differentiation from the diabase magma. Frequently the aplite grades into diabase along the walls; at other times it is sharply defined against the diabase walls. Some veins show aplite next to the diabase, followed by a layer of crystallized quartz, the crystals of which extend into the calcite which may occupy the centre of the vein. This type of vein commonly carries some native silver, smaltite and niccolite. The silver in the aplite and diabase is generally in thin scales or sheets. The occurrence of the diabase, aplite and quartz, successively, points to differentiation, whereas the calcite and the ores have come in later, probably from the same source.

The aplite type of vein, however, varies greatly in the arrangement of the constituent parts, the calcite and ores often being irregularly distributed in the aplite.

Chemical Data.—The trend of differentiation of the diabase in the Cobalt area follows remarkably closely the trends established for intrusives of similar chemical composition found elsewhere in the world. Perhaps the best example to be cited is the Skaergaard mass in Greenland, which was investigated by Wager and Deer. During crystallization differentiation, marked relative and absolute enrichment of FeO is followed by an equally marked enrichment of $Na_2O + K_2O$, the later exemplified by the small acidic dikes that the authors consider to be the latest differentiates of an originally saturated basaltic magma. A similar although less pronounced trend is evident in the Nipissing diabase sheet at Cobalt. The enrichment of FeO relative to MgO and to $Na_2O + K_2O$ is less marked than in the Skaergaard mass, but the enrichment in $Na_2O + K_2O$ that follows is very strong. Thus, the available chemical data strongly indicate that the aplite is a normal product of differentiation of saturated basaltic magma and is in all probability not formed by hydrothermal alteration (by solutions unrelated to the diabase) of the diabase along fractures.

The Ore-Bearing Solutions.—The metallic minerals within the aplites west of Bass Lake are closely related genetically to the aplites. The presence of the vug-like masses described above is especially important in that a complete sequence from aplite to the metallic minerals is evident in one hand specimen. The material filling the vugs was an integral part of the aplitic magma and as crystallization proceeded upon the emplacement of the magma, the crystallization of the major portion of the aplite was followed by segregation of a residual liquid rich in volatile components. As the temperature decreased albite, and slightly later, quartz crystals grew inward from the vug walls. The crystallization of carbonate and metallics followed with some replacement of the comb quartz and albite until the vug was completely filled. The system was apparently open and permitted additional material to be brought in to fill the vug completely.

The replacement type of mineralization is but a slight modification of the above sequence. If segregation of late residual liquid of the aplitic magma was able to migrate along the structures occupied by aplite, replacement of aplite occurred in a somewhat irregular manner and the replacement type of mineralization resulted.

Bastin has noted a feature of the veins of the Cobalt region that has a further bearing on the present problem. He cites (1, p. 718, 728, 729) a number of instances where the rock immediately adjacent to veins has been albitized. The albite has, in turn, been altered to calcite. It would seem that the early solutions moving through the fissures were sodic.

CONCLUSIONS

Several kinds of mineralization are known in the Cobalt district. Recently attention has been directed to a pervasive type of sphalerite-galena replacement, affecting principally the Keewatin rocks but occurring also in rocks of

the Cobalt series and indicating clearly a post-Cobalt age. The main cobalt-silver mineralization of the camp is in the form of clear-cut fissure veins with carbonate gangue. These veins cut rocks containing the earlier zinc-lead mineralization. This mineralization is substantially later than the diabase, as veins occur in faults that displace the diabase. A third kind of mineralization, which is the subject of this paper, is closely related to the aplites. This has not as yet proved to be of commercial importance. The mineralized aplites are, in turn, a product of the last stage of crystallization of the diabase sheet and show that normal processes of differentiation that segregate an aplite magma also bring about a concentration of Co and As as well as some other ore-forming elements. Because differentiation within the sheet is capable of producing on a small scale a late residual liquid that deposited minerals so closely similar to those that form the ore deposits, it is logical to think that the main cobalt-silver veins of the district were also derived from a diabase magma —the parent diabase magma from which the diabase sheet at Cobalt is but a small offshoot.

Department of Geology,
Princeton University,
Princeton, N. J.,
and
Stanolind Oil and Gas Co.,
Calgary, Alberta,
Canada

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AN OCCURRENCE OF MINERALIZED ORGANIC MATERIAL IN NOVA SCOTIA

ROBERT G. WIESE, JR.

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ABSTRACT

A small deposit of mineralized coalified material in the upper Mississippian Ardness formation is exposed on the northwest shore of Cape George, Nova Scotia. The principal sulfides are pyrite and chalcocite accompanied by lesser amounts of bornite and other basemetal sulfides. Textural relations indicate that the ore minerals have intricately replaced the cell structure of organic matter occurring in a permeable horizon.

It is suggested that the sulfides were introduced into a reducing environment created by decaying organic material, and were deposited either by adsorption, or by chemical reaction.

INTRODUCTION

THIS paper describes an example of sulfide replacement of cellular wood structure. The occurrence is of interest because the ore textures resemble many of those described in the replacement of organic material by uranium minerals in the Colorado Plateau (4, 12, 13, 14), and by copper minerals in deposits of the Red Bed type (5, 6, 8, 9, 10, 15, 16).

The problems posed by mineralized organic matter encompass many uncertain aspects of the formation of ore deposits: (1) What is the nature of the ore fluids? (2) What are the temperature and pressure conditions favorable for precipitation of ore minerals? and (3) What chemical environments exist at the site of deposition?

LOCAL GEOLOGY AND LITHOLOGY

The specimens were taken from an outcrop on the northwest shore of Cape George, Nova Scotia, roughly one half mile northeast of Knoydart Point,

Antigonish County. The rocks exposed are members of the upper Mississippian Ardness formation, which is part of the Windsor series. The Ardness rocks are overlain by 1000 feet of Pennsylvanian strata, which, in turn, are overlain unconformably by 50–60 feet of Quaternary rocks (17, p. 52).

Locally, the Carboniferous strata strike approximately north and dip 20 to 30 degrees west. The igneous rocks exposed in the area are lower Mississippian intrusive diabase sheets. Other than tilting, the strata show no appreciable deformation. For a detailed description of the stratigraphy, the reader is referred to the paper by Williams (17).

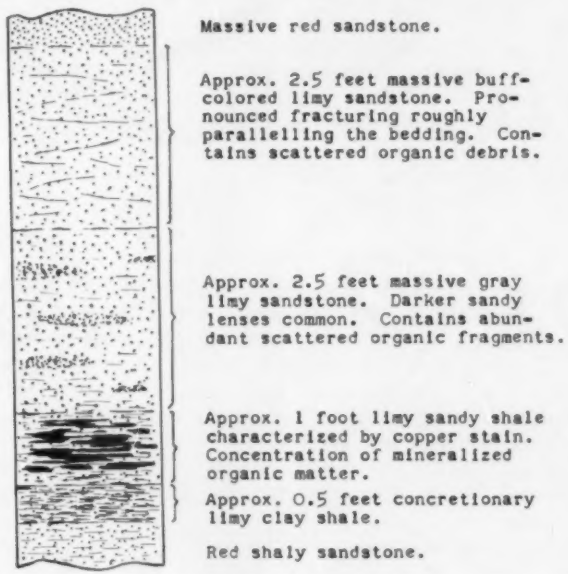
Massive red sandstone.
Approx. 2.5 feet massive buff-colored limy sandstone. Pronounced fracturing roughly parallelling the bedding. Contains scattered organic debris.
Approx. 2.5 feet massive gray limy sandstone. Darker sandy lenses common. Contains abundant scattered organic fragments.
Approx. 1 foot limy sandy shale characterized by copper stain. Concentration of mineralized organic matter.
Approx. 0.5 feet concretionary limy clay shale.
Red shaly sandstone.

Figure 1. -- Stratigraphic section of the outcrop.

FIG. 1.

The strata of the outcrop are exposed for a thickness of 6.8 feet, and consist of red sandstones, buff-colored limy sandstones, limy argillaceous shales, and red shaly sandstone. Fragments of fossilized carbonaceous debris are abundant throughout much of the sandstone. A notable concentration of coalified woody material occurs in a zone of shaly and limy sandstone approximately 1 foot thick and characterized by blue and green copper carbonate staining. The organic fragments range in size up to 8 inches long and 1.5 inches thick, and are flattened parallel to the bedding. Many of the fragments

resemble bark material, and some have undergone sulfide mineralization, which has resulted in the replacement texture to be described. A stratigraphic section of the outcrop is given in Figure 1.

Examination of handspecimens under a binocular microscope reveals no appreciable mineralization in other parts of the outcrop. Negative scintillation counter tests for radioactivity and negative ultraviolet light tests for fluorescence indicate that no uranium minerals are present.

MINERALIZATION

Microscopic examination of polished sections shows that sulfides have replaced organic debris. The sulfides observed include pyrite, bornite, chalcopyrite, tetrahedrite-tennantite, sphalerite, galena, chalcocite, and covellite. The presence of tetrahedrite-tennantite solid solution was confirmed by positive microchemical tests for both arsenic and antimony. The copper sulfides have been partly oxidized to azurite and malachite. Calcite cements the original detrital quartz grains.

The sulfide mineralization appears to be restricted to the carbonaceous material and to the locally associated original sediments.

TEXTURES

Mineralization of Organic Material.—The most notable texture seen in the polished sections is the cell by cell replacement of the coalified wood structure by the sulfides (Figs. 2, 3, 4). The cell walls have been replaced by pyrite. Normally, cell walls are thin structures (note the illustrations in references 1 and 2). The thickened appearance of the pyritized cell walls may result either from forced expansion of the walls by the introduction of pyrite, or from continued accretion of pyrite about numerous centers of nucleation as replacement progressed. Figure 2 shows distinct preservation of the cell divisions between replaced cells, indicating that replacement was a cell by cell process.

The lumens of the cells commonly are partly replaced by chalcocite. A carbonaceous residue occurs with the chalcocite where replacement is not complete. This residue may have resulted from the extrusion of carbonaceous material during replacement. Silica is known to extrude organic matter in the lumens during replacement of woody structures (E. S. Barghoorn, personal communication). In more advanced stages of replacement (Fig. 4), the lumens are almost completely filled with chalcocite, and the chalcocite replaces the pyritized cell walls. This suggests that chalcocite was introduced later than the pyrite. In places, bornite accompanies chalcocite replacement of the lumens. Apparently, the organic material of the lumens was more susceptible to replacement by chalcocite than was the pyrite.

Figure 5 shows pyrite replacing the cell walls of compressed woody material, having the appearance of numerous "drag folds." Nearly all other organic material has been replaced by chalcocite.

Figure 6 shows chalcocite blebs throughout carbonaceous material. Possibly the original organic matter had been sufficiently degraded to have been

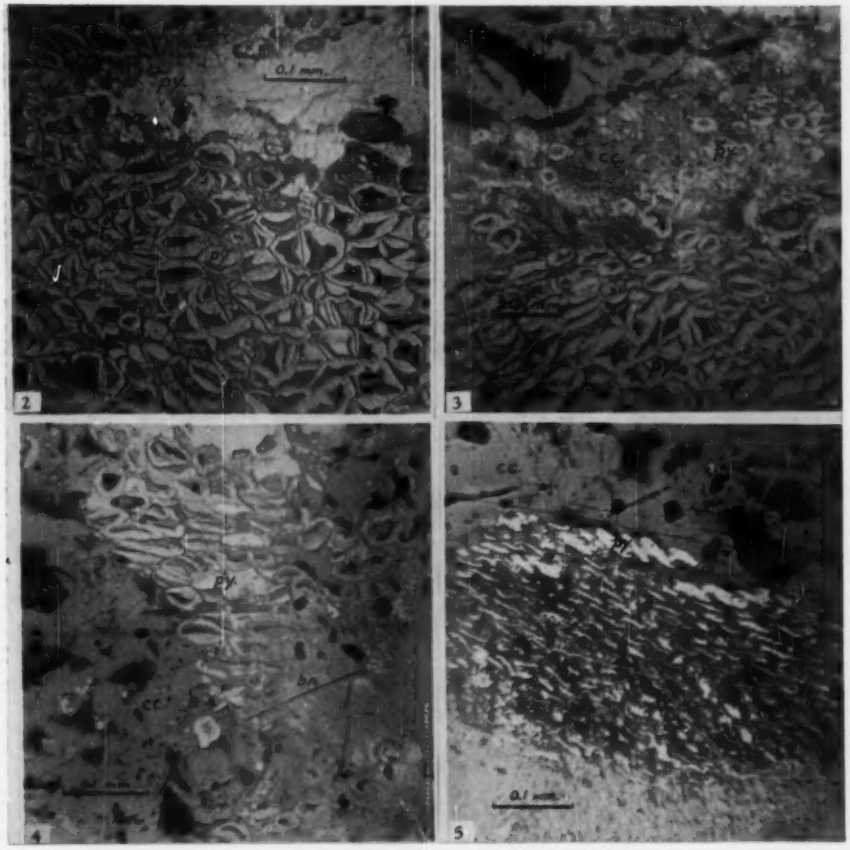

FIG. 2. Replacement of cell structure by pyrite and chalcocite. Note the preservation of the original cell divisions, and the organic residue (black) in the cell lumens.

FIG. 3. Replacement of cell structure by pyrite and chalcocite.

FIG. 4. Replacement of cell structure. In the advanced stage of replacement, chalcocite replaces pyrite of the cell walls.

FIG. 5. Replacement of compressed cell structure by pyrite. Note massive chalcocite in the upper portion of the picture.

an organic "gel" at the time of the chalcocite mineralization. This "gel" was then selectively replaced by chalcocite.

Other Textural Relations.—Pyrite and chalcocite are by far the most abundant sulfides. Where the pyrite is massive, it has been laced by chalcocite veinlets (Fig. 2). Figure 5 shows a front between chalcocite and pyrite. From this front chalcocite stringers transgress the pyrite. Bornite appears

to have formed at the interface between the pyrite and the chalcocite as a result of a reaction of the type:

$$2\ FeS_2 + 5\ Cu_2S = 2\ Cu_5FeS_4 + S.$$

Elsewhere in the polished sections bornite forms bladed intergrowths with chalcocite that resemble polysynthetic twinning. This suggests essentially simultaneous deposition.

The tetrahedrite-tennantite occurs as small blebs enclosed in the chalcocite and, also, peripheral to the chalcocite. Covellite is rare and occurs dominantly as small highly birefringent blebs in the chalcocite. Trace amounts of chalcopyrite occur associated with pyrite-chalcocite interfaces.

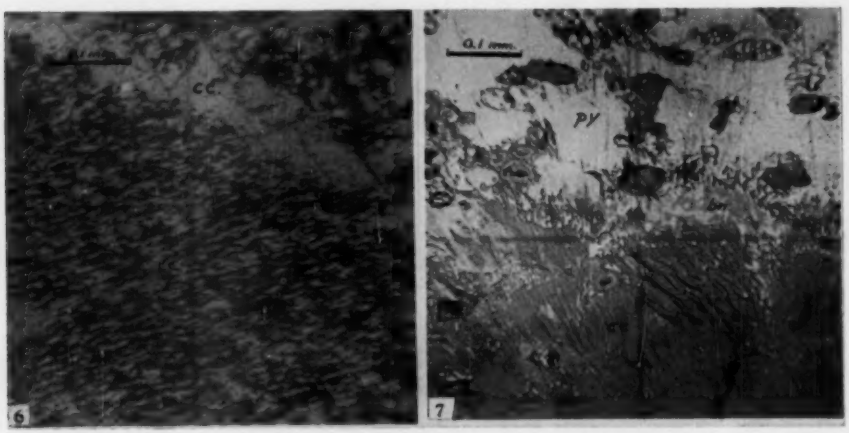

FIG. 6. Replacement of organic "gel" by chalcocite.
FIG. 7. Interface between chalcocite and pyrite, showing bornite. Note the cell structure completely replaced by chalcocite except for an organic residue.

Sphalerite occurs both as blebs within the chalcocite and as rims peripheral to chalcocite blebs. Galena is rare and generally occurs close to interfaces between chalcocite and unmineralized material.

Where organic material is locally absent, sulfide mineralization appears to have attacked the calcite cement of the rock. The detrital quartz grains are generally intact, except for minor peripheral replacement. Interstitial staining by copper carbonates is visible under inclined light.

Conclusions.—It is evident that the sulfides have been introduced into a shaly and limy sandstone containing abundant organic matter, which served as the chief control causing precipitation of the sulfides. Pyrite was the first sulfide deposited, followed by the copper sulfides. The textural relations suggest that the various copper sulfides are essentially contemporaneous, and earlier than sphalerite and galena.

POSSIBLE ORIGIN OF THE DEPOSIT

The mineralization has clearly been controlled by organic matter occurring in a relatively impermeable horizon. Organic debris occurring in more sandy members is not replaced, suggesting that the degradation and coalification of the plant remains in the less permeable shaly horizon was retarded relative to that of organic matter elsewhere. The solutions assisting the chemical breakdown of the material were hindered by this impermeability. Thus, solutions carrying the metal ions may have traversed the entire section with deposition of the sulfides taking place only where organic matter in a receptive stage of decay was abundant.

The conditions of temperature and pressure at which mineralization occurred is unknown. However, there is no reason to believe that either was very high. No source of magmatic heat is evident, and pressure sufficient to cause collapse of cell structure as shown in Figure 5 could be provided by a load of as little as 30 feet of sedimentary cover (E. S. Barghoorn, personal communication). As mentioned earlier, the mineralized organic material is overlain by approximately 1,000 feet of younger Carboniferous strata. The unconformity between the Pennsylvanian and the Quaternary represents an unknown thickness of overburden, and consequently, a maximum depth of burial at the time of mineralization cannot be postulated, nor can the effect of depth of burial on the temperature.

When organic matter decays it normally produces a reducing environment in which degradation proceeds in a direction towards the formation of less complex organic substances. The paragenetic sequence of pyrite followed by chalcocite and then bornite and chalcopyrite may represent the effects of a progressively more reducing environment.

As mentioned earlier, similar controls have been reported in uranium occurrences in the Colorado Plateau. It is thought that the decaying organic matter is receptive to ore solutions for only a limited time, probably early in the degradation sequence (R. M. Garrels, personal communication). How long after its deposition the organic matter develops favorability, and how long this endures depend upon such factors as the amount of water available in the enclosing rocks, the microorganisms present, the rapidity of deposition of overburden, and the amount of heat present during degradation. This may, in part, explain the erratic distribution of uranium and Red Bed copper deposits.

Various mechanisms for the precipitation of sulfides and uranium minerals by reaction with organic matter have been suggested (7, 9, 11, 12, 16). They may be broadly grouped as follows: (1) adsorption, and (2) chemical reaction. The metal ions in solution may be precipitated as sulfides by organic decay products and adsorbed by decaying organic material.

Until more information is available as to the manner in which the metals are carried in solution, theories of precipitation of sulfides by any mechanism must remain speculative.

ACKNOWLEDGMENTS

The writer is indebted to Drs. E. S. Barghoorn, R. M. Garrels, and H. E. McKinstry, all of Harvard University, for their suggestions and assistance in

the preparation of this paper. The author also wishes to acknowledge Mr. Isadore Adler of the U. S. Geological Survey for X-ray fluorescence analyses of the sections, and Mr. Charles Fletcher for his skillful preparation of the polished sections.

HARVARD UNIVERSITY,
CAMBRIDGE, MASSACHUSETTS,
Aug. 9, 1956

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DISCUSSIONS

THE COLUMBITE-BEARING GRANITES, JOS PLATEAU, NIGERIA

Sir: I was most interested in the article entitled "Economic Geology of the Decomposed Columbite-Bearing Granites, Jos Plateau, Nigeria," by F. A. Williams and others. Although I would like to be among those to congratulate him on placing on record some most valuable work, I would, in a friendly way, like to take exception to his statement on p. 305 that we, in the publication he mentions, accepted the original outline of Dr. Falconer as being substantially correct.

Bulletin 19 was, in fact, a radical departure from previous thought. Falconer's work was of the highest order, but was done at a time when ring complexes were by no means as well understood as they are today, and he therefore very naturally failed to recognize certain fundamental aspects of the Nigerian Younger Granite geology. Falconer regarded the outcrops of granite as those of the batholith and of cupolas. He regarded the "felsites" as intrusive because he could not see how they could have reached their present position relative to other rocks by flowage.

We showed that the granitic rocks were sheeted, although we did not, at that stage, place on record the idea that there were different phases of the granite itself, which came in as separate and concentric sheets. We also showed, in the face of much opposition by other geologists—though now fully accepted, that the "felsites" were not intrusive, but were all lavas which had been dropped within ring fractures, which fully accounted for their position.

Falconer's mapping, done without any decent topographical maps, proved incredibly accurate, but he put all the Younger Granite suite under one color on the map. We sub-divided this into five different blocks. MacLeod has, of course, gone much further, and shown that there are over ten recognizable species and varieties on the Plateau alone.

Summarily, we substitute for Falconer's batholithic concept, mechanization of emplacement akin to cauldron subsidence which cannot fairly be regarded as accepting the original outline.

R. A. MacKay

115 Moorgate,
London, E. C. 2,
Sept. 15, 1956

THE GEOLOGY AND ORE DEPOSITS OF THE QUIRUVILCA DISTRICT, PERU

Sir: The carefully prepared exposition on the Quiruvilca (Peru) ore deposits by R. W. Lewis, Jr. (Econ. Geol., vol. 51, p. 41–63, 1956) has contributed to our understanding of the geology of northern Peru. As with many

operating mines, the continued exploration and development of the ore bodies allows greater appreciation of the old features, and often uncovers new ones. Active geologic field work, largely by the present junior writer, has paced exploration. Of particular interest to geologists in general is our interpretation of the possible relationships of certain local features to regional geology, especially mountain building processes.

We have found three sets of vein structures existing in the district (1) the main veins, striking N 65° E and dipping 80° SE, (2) minor veins, striking N 40° E and dipping 70° SE, and (3) vein-faults, striking E–W and dipping vertically. The direction of movement is indicated by striations on the vein walls as well as the numerous minor splits into the walls (see Fig. 1).

Now the general trend of the Andean mountain chain in northern Peru is about N 25° W. Casual spot observations indicate that the folding has a general axial trend of N 25° W and that thrust faults dip westerly. Figure 2 shows that Quiruvilca vein-fault structures superimposed on the trend of the Andean mountain ranges, giving the classic strained ellipsoid relations (see Fig. 2). It does not seem to us that this relationship is merely coincidental. A closer measurement of the age of mineralization is also possible.

Likewise of general interest is the presence of tourmaline. The mineral has been found scattered throughout the district and appears to have formed over a wide time interval. Tourmaline may occur in more mineral deposits than previously reported because it is easily overlooked.

L. P. Entwistle
V. F. Hollister

Lima, Peru,
Aug. 20, 1956

NOTES ON THE GEOTECTONICS AND URANIUM MINERALIZATION IN THE NORTHERN PART OF THE NORTHERN TERRITORY, AUSTRALIA

Sir: The excellent criticisms of "Geologese" that have appeared in past numbers of Economic Geology do not seem to have been wholly fruitful. May I add another protest against the rising tide of jargon obscuring geology, and suggest that hazy language is the product of hazy thought?

It is unnecessary in most cases to coin a mixture of corrupt Greek and English in order to express a simple idea; but if we do need a new term, let it be clearly defined, and let the coiner have due regard to the requirements of either language by consulting a dictionary. We have already had the bastard word "megashear" for a great shear; and "orocline" which presumably means a bend in a mountain or a bent or tilted mountain.

J. Rade's paper—Economic Geology, No. 4, 1956—offers just such a target for criticism. It is a welter of obscure or ill-defined words and tautological expressions. Let us examine a few. The word "tectonic" is an adjective meaning "of structure, structural"; and "tectonics" is accepted as a noun implying "structures"—the way the thing was built. It is applied ex-

clusively to structures of the earth's crust. Hence the prefix "geo-" is unnecessary, and is doubly redundant when the author writes of the geotectonic evolution of the world: γῆ meaning "world" or "earth."

Why use "geoplasma" in place of the long-established "magma," and just what are "germanotype tectonics"?

The author's handling of the word "orogen" is unfortunate. "Orogeny" means the birth or making of mountains, and orogenic movements are mountain-building movements. These words are used correctly in the last four lines of p. 355. But what is meant by an "orogen" and then, "formation of an orogen"? The terminal "gen" implies formation anyhow. If one must use Greek and not English, his paragraph (p. 358) should read: "after the orogenic phases the *oros* commences to break . . . " oros meaning mountain, mountain-range or -unit. In the remainder of this paragraph the word "orogen" is used as a noun seven times, and not once does it make sense. The word "mountain" is the proper one. This misuse and confusion of the term continues on p. 359.

The terms "bathyrheon" and "hyporheon" are regrettable, though one can at least perceive their meaning from their derivation. (Should it not be "bathyrhöon"?) But a "hyporheon" cannot build an "orogen." It can perhaps build a mountain or cause orogeny.

The expression "bathyrheal underflow" seems to please the author, for it occurs seven times on p. 360 and elsewhere too. It is a fine important-sounding phrase; and I suppose it to mean a stream or current of magma which drags at the base of the overlying crust. But the adjective "bathyrheal" itself means "of underflow" or "of a current flowing at depth"; why write about the underflowing underflow in Greek and English together?

The specific English word for a current flowing at depth is "undertow," and let us rewrite the last dreadful sentence of para. 4, p. 359, thus: "The undertow carried on its back the broken pieces of the mountain range derived from the geosyncline and the flow beneath it." It would be out of place for me to criticize the subject-matter of the paper, which is not offered for discussion. It goes far into the realm of cloudy hypothesis. It is therefore even more necessary that the author should attempt to convey his ideas with the utmost clarity, and there is no excuse for these imperfections of expression in the medium in which it is written.

D. W. Bishopp

Tabora, Tunganyika,
Sept. 17, 1956

REVIEWS

Ore Deposits. By I. G. MAGAK'YAN. Pp. 299; figs. 109. Gosudarstvennoe Nauchno-Tekhnicheskoe Izdatel'stvo Literaturi po Geologii i Okhrane Nedr, Moscow, 1955. Price, Rbl. 8.85.

The author's stated purpose is to describe the genetic types of ore deposits, the character of ores, their value, and the paragenetic associations of minerals. The book consists of six chapters dealing with 1) iron, titanium, manganese, and chromium; 2) rare and minor metals; 3) non-ferrous metals; 4) noble metals; 5) radioactive metals; and 6) rare earths, and disseminated metals. The description of each metal includes data about properties, uses, production and reserves (except for the Soviet Union), geochemistry, mineralogical composition of ore, technological requirements for the ore, genetic types of deposits and ore formations, metallogenetic provinces and epochs, principal deposits, and also a bibliography. The book does not cover all the major ore deposits of the Soviet Union. The description of many of them are substituted for by generalized, rather abstract, characteristics, even without indication of the location. However, the location of some of these deposits can be deciphered from the list of references which includes Russian publications dated as late as 1954. A special emphasis is laid upon the ore deposits of the free world, and America in particular.

The author did not, at the beginning of his handbook, present a general review of the new theories of metallogenesis advocated and fervently discussed by leading Russian geologists in current geological magazines. The book provides a certain interest in the sections where it deals with a few "unclassified" descriptions of deposits, illustrated with maps and cross-sections. It is noteworthy that a handbook on ore deposits prepared by a group of authors and edited by P. M. Tatarinov and A. G. Betekhtin in 1946 in Moscow, contains more descriptive material relating to the Soviet Union than the book reviewed. This situation reflects the trend to conceal information dealing with mineral resources. It is perhaps not the fault of the author that he does not actually give the complete picture of the latest developments in the field of economic geology in the Soviet Union, as he promised to do in the introduction, which evidently may be due to "circumstances beyond his control."

This handbook, although not complete, suggests that the supply of strategic minerals in the Soviet Union seems to be adequate for the requirements of the industry, especially if the mineral potential of Red China is taken into account.

The author has been lecturing since 1945 at the department of geology of the Mining Institute of Leningrad.

EUGENE A. ALEXANDROV

DEPARTMENT OF GEOLOGY,
COLUMBIA UNIVERSITY,
NEW YORK, N. Y.,
Nov. 26, 1956

The Metalliferous Mining Region of South-West England. By H. G. DINES. Memoirs of the Geological Survey of Great Britain, H. M. Stationery Office, London, 1956, 2 vols., 795 pp., 15 pl., 19 maps in pockets. Price, £5–5–0.

Of the 1,500 mines and prospects which once existed in the South-West of England only three properties are alive today, two in operation for tin and one for tungsten. But the mining region is a classical one, in which many fundamental concepts of economic geology were born, and thus has an interest out of all proportion to its present-day potentiality. The first thirty pages of Mr. Dines' memoir give a simple succinct summary of the geology and mineralogy of the vein deposits associated with the Hercynian granites, deposits which until the middle of last century formed the world's principal source of copper and which have yielded considerable more than two million tons of tin. These introductory pages should form obligatory reading for every student of economic geology. The remainder of the work, and by far its greater part, is occupied by descriptions of around 1,100 properties for which records are extant. "The account of each mine contains all the information it has been possible to obtain from past records, from an examination of the ground and, where possible, from the workings." Whether this encyclopaedic compilation of data will act as a spur to those enthusiasts in Britain who call for a revival of Cornish mining, or whether it will dampen their ardour, time alone will show.

C. F. DAVIDSON

UNIVERSITY OF ST. ANDREWS,
SCOTLAND,
Oct. 20, 1956

Les Gisements de Manganèse Volcanogènes de Tiouine. By J. BOULADON, G. JOURAVSKY, and C. COLSON. Pp. 180; plates 14; figs. 14; maps 12. Service Géologique de Maroc, Rabat, 1955.

The manganese deposits of Tiouine are the third most important deposits of French Morocco, with an annual output of 50,000 tons of metallurgical grade ore with an average manganese content of 44–45 per cent.

In describing the genesis of the manganese deposits of this Precambrian region, the authors have exhaustively discussed the geology of the region with the help of numerous paleogeographic maps illustrating the different distinct phases of volcanism and sedimentation encountered. The discussion is arranged in two parts. The first outlines the general geology and petrography of the volcanic series, surmounted by sedimentary continental detrital series, at the base of which the manganese beds are interstratified.

In the second part mineralogical data are reviewed and manganese minerals are defined in terms of composition and crystal structure. The most important manganese mineral of the Tiouine region is braunite. Associated with it are the minerals of the isostructural series, hollandite-cryptomelane-coronadite. They also mention the presence of polianite in the oxidized zone, but this mineral has already been shown to be identical to pyrolusite. These minerals constitute three main types of ore occurrence: (a) Quartzose nodules and mineralized barite impregnations in the ignimbrites and lavas, (b) replacement in ignimbrites and lavas, (c) and veins.

Although much has been written about the origin of various types of manganese deposits, very little is added by the authors as to the genesis of stratiform deposits. However, presentation of a few new ideas gathered mostly from recent Russian

publications, with a few short summaries form a valuable part of the memoir.

In regard to the origin of the manganese deposits of Tiouine basin, the authors feel that the "epithermal-sedimentary" hypothesis best accords with the facts. These epithermal-sedimentary deposits are similar in many respects to the "exhalative-sedimentary" deposits of H. Schneiderhöhn, the "volcanic-subaquatic" deposits of P. Niggli, and the volcanogenous-siliceous deposits of N. Chatsky.

An up-to-date bibliography, including many Russian publications, makes this book very useful to students interested in the study of manganese deposits.

B. L. SREENIVAS

YALE UNIVERSITY,
NEW HAVEN, CONN.,
Dec. 1, 1956

The Ground Water Resources of Westchester County, New York; Part I, Records of Wells and Test Holes. By E. S. ASSELSTINE and I. G. GROSSMAN. Pp. 79; figs. 1; maps, 3; tables 3. State Water Power and Control Commission, Albany, N. Y., 1955.

This bulletin is Part I of a two-part report. It includes an introduction and a brief mention of general geologic and hydrologic features, followed by 69 pages of tables including drillers' logs of selected wells, test holes, and records of the same, and an index of wells by owners. The maps show the location of wells and test holes in Northwestern, Northeastern, and Southern Westchester County. It is a useful body of information to dwellers in Westchester County.

Petrographic Modal Analysis. By FELIX CHAYES. Pp. 113; figs. 14. John Wiley & Sons, Inc., New York, 1956. Price, $5.50.

All petrographers know of the Chayes method of modal analysis. This book grew out of a series of lectures before a graduate seminar in petrology at the California Institute of Technology in 1955. Much of it has not been published before, and this book is the only single work covering the whole subject. The author states he has attempted to give the student "(a) a clear description of the geometrical basis of the method; (b) a review and summary of the techniques and instrumentation; (c) a careful discussion of reproductability; (d) a definition and numerical characterization of analytical error; (e) a sense of the importance of analytical error in the design and planning of sampling experiments." The first three of these are covered in his chapters 1–6. Chapters 7 to 10 deal with a particular rock type in which errors, coarseness of grain, standards, limitations, are dealt with. Chapter 11 is entitled "The Holmes Effect and the Lower Limit of Coarseness in Modal Analysis." This is followed by two appendices, one on statistical references, and the other on a simple method of calculating z.

The book is a convenient brief reference which must become a hand book for every student of petrology.

California and the Southwest. CLIFFORD M. ZIERER, Editor. Pp. 376; illus. John Wiley & Sons, New York, 1956. Price, $11.25.

This large comprehensive regional study of the area composed of California, Nevada, Arizona and Utah presents information in regard to its resources, its growth, and gives a complete picture of the Southwest. It is written by thirty-one other contributors, whose works have been carefully organized and edited by the editor-in-chief.

The book is divided into two parts. Part I, The Physical Characteristics of the Region, takes up the major land form divisions of California and the Southwest interior. It covers weather, climate, water resources, soil resources and management, vegetation, animal life, and the ocean off the California coast. This takes up eighty pages. Part II is entitled The Cultural Characteristics of the Region and is divided into six parts. The first deals with Indian occupancy and early white settlement; the second deals with agricultural activities; the third deals with other kinds of resource use; the fourth deals with manufacturing industries; the fifth, with transportation and trade; and the sixth, with population patterns and political relationships.

The work is an unusually broad picture extending from the coast off California to the central area, and from the early history of the first settlements to questions of water supply and power. Each chapter stands as a complete coverage of a given topic and so is a complete essay on that particular subject. The book is well illustrated and nicely printed and should serve as a general reference for all those interested in the Southwest from the standpoint of its resources and its geography.

Mines Register, Successor to the Mines Handbook and Copper Handbook. Vol. 25. Pp. 784. Mines Register Co., 425 West 25th Street, New York 1, N. Y., 1956. Price, $25.00.

This Mines Register in its 25th edition follows the general procedure of its predecessors. It contains the latest information obtainable on 5000 mining companies that are located in the Western Hemisphere, which produce precious, semiprecious, and base metals. Important mining companies located in other parts of the world are included in a special section. All of the mining companies are listed alphabetically. The information concerning each company was obtained either from the company itself or from sources that were deemed reliable. Some information received too late is to be found in the Addenda immediately following the section devoted to foreign mines. As before, also, there are sections on 20,000 dormant mines, and statistics on copper, gold, lead, silver, zinc, and security prices. A comprehensive buyers' guide section follows at the end.

The new Register will, as before, fill the needs of mining companies, investment houses, and all others interested in the mining industry.

Clays and Clay Minerals. Edited by W. O. MILLIGAN. Pp. 573; illus. National Academy of Sciences—National Research Council Pub. 395. Washington, D. C., 1955. Price, $7.00.

This book is made up of 43 pages by 69 contributors. The subject matter covers a very large range including geology, mineralogy, soil chemistry, soil physics, soil mechanics, physics, colloidal chemistry, and ceramics. The papers deal with electron microscopy, electron defraction, physical properties, crystallography and other varied subjects. Some excellent electron microphotographs are very well reproduced on full size pages, particularly in the first two articles—one on Electron Microscopy of Clay Surfaces, by Thomas F. Bates and J. J. Comer and the second on A Study in Morphology by Electron Defraction, by L. F. Sand and J. J. Comer. Also, a third one on Electron Micrographic Studies of Clays, by M. S. Taggert, Jr., W. O. Milligan, and H. P. Studer. Other of the many papers include topics such as Identification of Clay Minerals, Swelling of Clays, Ionic Exchange Capacity, Viscosity, Peptization Resistance, Hydrogen Iron, Catalysis, Effects of Heat and Acid Treatment.

This conference was jointly sponsored by the Committee on Clay Minerals of the National Academy of Sciences—National Research Council, and the Rice Institute. It institutes an extremely important contribution to the literature on clays and clay mineralogy and will be invaluable to all students of sedimentation and sedimentary petrography.

BOOKS RECEIVED

V. RAMA MURTHY

Coalmining. I. C. F. STATHAM. Pp. 575; figs. 310. Philosophical Library, New York, 1956. Price, $15.00. *Very well written and amply illustrated, this book serves to introduce all the aspects of coal-mining to a beginner. Emphasis is on the practical side, rather than on lengthy theoretical discourses, and interest in the subject matter is kept up by the clear style and good figures and diagrams. Chapters include also the geology of coal, importance of coal mining in the economy of a nation, safety and health of the workers, and other such social welfare topics.*

Plant Physiology. MEIRION THOMAS in collaboration with S. L. RANSON and J. A. RICHARDSON. Pp. 692; figs. 89. Philosophical Library, New York. Price, $12.00. *This fourth edition is a very thoroughly modernized version of its predecessors. Major changes have been made to include recent advances in plant physiology, in subjects such as photoperiodism, vernalization, chromotography and the use of isotopes as tracer atoms. This book will serve as an excellent modern text book on plant physiology.*

The Australian Mineral Industry, Quarterly Review and Quarterly Statistics. Pp. 21; tbls. 9. Bureau of Mineral Resources, Geology and Geophysics, Melbourne, 1956. *Mineral statistics for quarter ending March 31, 1956, and the review of information up to August, 1956.*

Annual Report, 1955. Bechuanaland Protectorate Geological Survey Department. Pp. 46; pls. 4; figs. 4; provisional geological map, 1 inch = 50 miles. Parow, Cape, South Africa, 1956. *Geology of some areas in the Protectorate, and other mineral data.*

Congo Belge et Ruanda-Urundi Service Geologique. Bull. 6, Fac. 1–6. Leopoldville, 1956.

Aguas Minerais do Brasil. RENATO SOUZA LOPES. Pp. 148. Serviço de Informação Agrícola, Rio de Janeiro, 1956.

Studies of Mississippian Algae. J. H. JOHNSON and KENJI KONISHI. Pp. 133; pls. 24; figs. 2; tbls. 5; maps 6. Quart. Colorado School of Mines, Vol. 51, No. 4, Golden, 1956. Price, $1.50. *Summary of our present knowledge of the fossil algae of Mississippian age.*

Colonial Geology and Mineral Resources, Vol. 6, No. 2. E. H. BEARD, Ed. Pp. 272; pls. 9; figs. 13. Colonial Geological Surveys, London, 1956. *Contains several interesting articles, scientific notes, select bibliography on geology of the mineral industry, and mineral and metal statistics. Well compiled quarterly bulletin.*

Chemical Analyses of Igneous Rocks, Metamorphic Rocks and Minerals 1931–1954. E. M. GUPPY and P. A. SABINE. Pp. 78; tbls. 43. Geological Survey, Great Britain, London, 1956. Price, 10s. 6d. net.

The Closepet Granites of Mysore State, India. B. P. RADHAKRISHNA. Pp. 118; pls. 11, tbls. 4. Mysore Geologists' Assoc., Bangalore, 1956.

Study on the Industrial Method of Perfect Utilization of Mineral Resources. HIDESABURO KURUSHIMA. Privately printed, Japan, 1956. Pp. 83; pls. 66; figs. 69; tbls. 136. *This treatise elaborates the painstaking efforts and results of the author, to utilize pyrite for the production of sulphuric acid. With very good photographs, flow sheets and other information, the book is a faithful record of all experiments conducted by the author. The style of English could have been better, but that does not detract from the technical value of the book.*

Rapports et Bilans de l'Exercice 1955, Comité Spécial du Katanga. Pp. 174. Brussels, 1956. *Reports and statement of accounts.*

The Geology of New Hampshire, Part II: Bedrock Geology. M. P. BILLINGS. Pp. 203; figs. 20; tbls. 12; geological map of New Hampshire in pocket. New Hampshire State Planning and Develop. Comm., Concord, 1956.

Forty-fourth Annual Report State Inspector of Mines. J. A. GARCIA. Pp. 66. Albuquerque, New Mexico, 1956. *Mineral statistics.*

Ontario Dept. Mines, Sixty-fourth Annual Report, Vol. 64; Pt. 5, 1955: Geology of the Miller Lake Portion of the Gowganda Silver Area. E. S. MOORE. Pp. 41; pls. 14; figs. 9. Toronto, 1956.

Ontario Fuel Board, Second Annual Report, 1955. Pp. 145, pls. 3; figs. 3; tbls. 22. Toronto, 1956. *Complete review of the operation of the Natural Gas and Petroleum industry in the Providence of Ontario for 1955.*

Ferruginous Bauxite Deposits in the Salem Hills, Marion County, Oregon. R. E. CORCORAN and F. W. LIBBEY. Dept. Geology and Mineral Industries, Bull. 46, Portland, 1956. Pp. 55; pls. 13; figs. 8; tbls. 9. *Low grade, low-silica bauxite is available in considerable quantity and may be good potential ore, in view of cheap surface mining and good transportation.*

Some Uranium Occurrences in West Texas. D. H. EARGLE. Pp. 23; figs. 4; tbls. 3. University of Texas Bureau of Economic Geology, Austin, 1956. *Uranium minerals have been found at several localities in west Texas.*

Geologic Atlas of Utah: Emery County. W. L. STOKES and R. E. COHENOUR. Pp. 92; pls. 38. Utah Geol. and Mineral. Surv., Bull. 52, Salt Lake City, 1956.

Revista de Minas e Hidrocarburos. Pp. 69. Republica de Venezuela Ministerio de Minas e Hidrocarburos, Caracas, 1956.

Titanium. A. A. PEGAU. Pp. 17; fig. 1; tbls. 7. Virginia Div. of Mineral Resources Circ. No. 5, Charlottesville, 1956. *Compilation data of Titanium minerals, production, with special reference to deposits in Virginia.*

The Goose Egg Formation (Permo-Triassic) of Eastern Wyoming. C. A. BURK and H. D. THOMAS. Pp. 11; figs. 2. Geological Survey of Wyoming, Rept. of Investigations No. 6, Laramie, 1956. *Formal proposition of a new formational name.*

Manual on Geophysical Prospecting with the Magnetometer. J. WALLACE JOYCE. Pp. 129; figs. 53. Hobart Publishing Co., Washington 15, D. C. Reprinted by permission U. S. Bureau of Mines. *Techniques of using the Schmidt-type magnetometer. Complete and exhaustive manual.*

Geophysical Activity in 1956. Interim Report to Midyear. H. G. PATRICK. Pp. 17; figs. 10; tbls. 3. Society of Exploration Geophysicists.

Brazilian Department of Mineral Production—Rio de Janeiro, 1950–54.

Determinação do gráo de liberação dos minerais, por meio de platina integradora de Shand. EVALDO OSORIO FERREIRA. Pp. 39; pls. 13; figs. 5; tbls. 2. Avulso 9.

A Soda Eletrolítica e a Produção do Fosfato Dicálcico. MÁRIO DA SILVA PINTO. Pp. 66; figs. 10; tbls. 12. Boletim 37.

Service des Mines du Cameroun, Paris, 1956.

Notice Explicative sur la Feuille Yaoundé-est. G. CHAMPETIER DE RIBES and M. AUBAGUE. Pp. 35; fig. 1; tbl. 1; Geologic map 1:500,000.

Bulletin de la Direction de Mines et de la Géologie. Notice explicative par J. GAZEL, V. HOURCQ et M. NICKLES. Pp. 62; with geologic map 1:1,000,000.

Illinois Geological Survey—Urbana, 1956.

Circ. 220. Unpublished Reports on Open File, IV. Stratigraphy and Areal Geology. LOIS KENT. Pp. 19. *Annotated bibliography of unpublished reports.*

Circ. 221. Sampling Limestone and Dolomite Deposits for Trace and Minor Elements. J. E. LAMAR and K. B. THOMSON. Pp. 18; figs. 5. *Sampling technique of limestone and dolomite deposits for trace element analysis suggested.*

Circ. 222. Groundwater Geology in Western Illinois, North Part. A Preliminary Geologic Report. R. E. BERGSTROM. Pp. 24; figs. 6; tbl. 1. *Summary of groundwater principles and discussion of methods of developing groundwater supplies in the area.*

Circ. 224. Studies of Waterflood Performance, II. Trapping Oil in a Pore Doublet. WALTER ROSE and P. A. WITHERSPOON. Pp. 13; figs. 4. *Study of pore doublet as a model of reservoir rock and the rather startling conclusion that oil tends to be trapped in the smaller tube of the pore doublet.*

Geological Survey of Japan—Hisamoto-cho, Kawasaki-shi, 1956.

Explanatory Text of the Geological Map of Japan. Tsuno (Kagoshima-61). YOSHITO KINO. Pp. 26; pls. 7; figs. 2; tbls. 1. *Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Tomitaka (Kagoshima-53). TAMOTSU NOZAWA and YOSHITO KINO. Pp. 28; pls. 9; figs. 2; tbl. 1. *Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Kainan (Kyoto-88). KEN HIRAYAMA and KEISAKU TANAKA. Pp. 76; figs. 11; tbls. 2. *Geologic map, 1:50,000.*

Explanatory Text of the Geological Map of Japan. Todorogi (Kyoto-89). KEN HIRAYAMA and KEISAKU TANAKA. Pp. 50; figs. 5; tbls. 5. *Geological map, 1:50,000.*

Geological Survey of Kansas—Lawrence, 1956.

Bull. 122. Oil and Gas Developments in Kansas During 1955. E. D. GOEBEL, A. L. HORNBAKER, W. R. ATKINSON, and J. M. JEWETT. Pp. 249; pls. 3; figs. 3; tbls. 58. *Proved reserves of Kansas crude oil at the end of 1955 were 998.1 million barrels. Proved reserves of natural gas were about 16.3 trillion cubic feet.*

Bull. 123. Stratigraphy of Pre-Marmaton Desmoinesion (Cherokee) Rocks in Southeastern Kansas. W. B. HOWE. Pp. 132; pls. 10; figs. 8.

Mysore Geologists' Association—Bangalore, India, 1956.

Bull. 10. Fibrolite (Sillimanite) in the Migmatites of Tilatanr near Tetulmari (E. Ry.) Jharia Coalfield, Bihar. M. S. SADASHIVAIAH. Pp. 15; pls. 3; fig. 1. *Metasomatic origin proposed for the fibrolite in the migmatites of Tilatanr area.*

Bull. 10. Structure and Petro-Chemistry of the Chamundi Granites, Mysore State. M. R. SRINIVASA RAO. Pp. 17; pls. 5; fig. 1; tbls. 2. *Study of struc-*

tural relations and chemical relations of Chamundi granites indicates emplacement by magmatic intrusion.

North Dakota Geological Survey—Grand Forks, 1956.

Twenty-Ninth Biennial Report. W. M. LAIRD. Pp. 24; figs. 3.
Investigation of Lake Agassiz Clay Deposits. O. E. MANZ. Pp. 40; figs. 3; tbls. 5. *Good common brick, building or drain tile can be readily made from the silt and clay units of Lake Agassiz deposits.*

Oklahoma Geological Survey—Norman, 1956.

Vol. 16, No. 10. Some Facts about Oklahoma Uranium. N. M. CURTIS. Pp. 107–119; figs. 1–4; tbls. 1–2. *Recent discoveries and prospecting regulations for Uranium.*

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Geological Survey of Uganda—Entebbe, 1956.

Records of the Geological Survey of Uganda 1954. Pp. 71; pls. 9; figs. 8. *Six articles, on regional geology, electrical resistivity survey and absorptiometric analysis of beryl.*

Annual Report of the Geological Survey Department for the year ended 31st December, 1955. Pp. 35; tbls. 3; Appendices 5; map, 1:2,000,000. Mem. No. 9. Oil in Uganda. Pp. 33; figs. 6; appendices 2.

Geological and Economic Survey of West Virginia—Morgantown, 1956.

Bull. No. 13. Oil and Gas Report and Map of Monongalia, Marion, and Taylor Counties, West Virginia. O. L. HAUGHT. Pp. 51; pls. 2; figs. 2. *The possibilities of production of gas from deeper horizons are excellent. Discussion of previous development, structure and stratigraphy. Geologic map, 1:62,500.*

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Rept. of Investigations No. 13. Relation of Geology to Drainage, Floods, and Landslides in the Petersburg Area, West Virginia. V. T. STRINGFIELD and R. C. SMITH. Pp. 19; pls. 3; figs. 2; tbl. 1. *Water gaps formed by streams that cut across geologic structure, together with steep dip slopes and low permeability of formations are the causes for the floods in the area.*

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Bull. 1038. Geology and Mineral Resources of the Hudson and Maynard Quadrangles Massachusetts. W. R. HANSEN. Pp. 104; pls. 3; figs. 28. *Mineral resources of the area include surface and underground water, sand and gravel deposits, till, fine-grained lake-bottom deposits, crushed stone, granite, flagstone, marble and peat.*

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Prof. Paper 274-I. Additions to the Flora of the Spotted Ridge Formation in Central Oregon. S. H. MAMAY and C. B. READ. Pp. 211–266; pls. 34–37.

Prof. Paper 274-K. Stratigraphy of Middle Ordovician Rocks in the Zinc-Lead District of Wisconsin, Illinois, and Iowa. A. F. AGNEW, A. V. HEYL, JR., C. H. BEHRE, JR., and E. J. LYONS. Pp. 251–312; figs. 31–54. Price, 60 cts.

Water-Supply Paper 1109. Ground-water Geology of the Coastal Zone, Long Beach-Santa Ana Area, California. J. F. POLAND, A. M. PIPER, ET AL. Pp. 162; pl. 8; figs. 2; chart 1; tbls. 6. *The principal body of fresh ground water occurs at 800–2600 ft. below sea level.*

Water-Supply Paper 1360-B. Ground Water in Northeastern Louisville, Kentucky. M. I. ROBABAUGH. Pp. 169; pl. 2–18; figs. 4–28; tbls. 8. *Total ground water storage in a 3-square-mile area along the Ohio River northeast of Louisville, Ky., is estimated as 7 billion gallons.*

Water Supply Paper 1364. Water Resources of Southwestern Louisiana. P. H. JONES, E. L. HENDRICKS, BURDGE IRELAN, ET AL. Pp. 460; pl. 38; figs. 73; tbls. 31. *Fresh ground water occurs to a maximum depth of 3100 feet in Southwest-*

ern Louisiana. Except during flood periods, the water in the Calcasieu River from Lake Charles downstream is too saline for rice irrigation. Potential ground water supply of the area is several times as great as the maximum recorded withdrawal.

Water-Supply Paper 1367. Ground-Water Geology of Parts of Laramie and Albany Counties Wyoming, and Weld County, Colorado. H. M. BABCOCK and L. J. BJORKLUND. Pp. 61; pl. 1; figs. 12; tbls. 4. Price, 50 cts. *The unconsolidate alluvium and terrace deposits in the Carpenter-Hereford-Groves area probably are the only aquifers in the area in which additional wells may be developed.*

Water-Supply Paper 1373. Sedimentation and Chemical Quality of Surface Waters in the Wind River Basin, Wyoming. B. R. COLBY, C. H. HEMBREE, and F. H. RAINWATER. Pp. 336; pl. 12; figs. 45; charts 3; tbls. 100.

SOCIETY OF ECONOMIC GEOLOGISTS

The Penrose Medal of the Society of Economic Geologists was awarded to Donnel Foster Hewett. The award took place at a banquet of the Society in Mexico City, September 8, 1956, during the 20th International Geological Congress, when members from many countries of the world could be present. The presentation was made by Felix Wormser who paid tribute to the outstanding contributions made by Dr. Hewett during his long service with the U. S. Geological Survey, from which he has not been able to retire. He has long been an Associate Editor of the journal, ECONOMIC GEOLOGY, and for many years was the President of the Economic Geology Publishing Co. Dr. Hewett is a present preparing a monograph on Manganese, embodying his life-long experience with occurrences of this ore. About 150 persons attended the banquet in his honor.

Olaf N. Rove, who has served as Secretary of the Society of Economic Geologists since 1946, submitted his resignation to the Council on October 18, 1956. Dr. Rove believes that it would be in the best interest of the Society for him not to continue as its Secretary, because the pressure of his private work and frequent absence, is limiting the amount of time he can give to the Society's affairs.

The Council accepted Dr. Rove's resignation with great regret but with appreciation of the responsibility he had accepted for the past ten years, and with the realization that it could not, under the circumstances, ask him to continue. After considering a number of candidates to assume the Secretaryship, the Council appointed Dr. Harold M. Bannerman.

Dr. Bannerman was born at Barney's River, Nova Scotia, Canada. His undergraduate training was at Acadia University, Nova Scotia, followed by graduate work at Princeton leading to his Doctorate in 1927. During the next fifteen years, he was on the faculty of Dartmouth College. He served on the New Hampshire State Planning and Development Commission from 1940 to 1942. He also was on the staff of the Canada Geological Survey from 1927 to 1930, and later was active in consulting work in Canada and the United States. He was granted United State citizenship about 1935.

In 1941 Dr. Bannerman joined the U. S. Geological Survey as a specialist on pegmatites. As his responsibilities increased, he was appointed Assistant Chief Geologist in charge of the Economic Division in 1948, and in 1953 as Assistant Chief Geologist for programing of the Geologic Division.

Dr. Bannerman is a Fellow of the Geological Society of America, member of The American Institute of Mining, Metallurgical and Petroleum Engineers, the Arctic Institute of North America, Geological Society of Washington, and Cosmos Club of Washington. In addition to mineral deposits, he is also particularly interested in the geology of pegmatites and problems of Precambrian geology and has written numerous papers on these subjects. Dr. Bannerman will take over as Secretary with the beginning of the 1957 Society year on April 1, 1957. His address is Care of U. S. Geological Survey, Washington 25, D. C.

SCIENTIFIC NOTES AND NEWS

The Chrestien Mica Gondwanaland Medal was awarded by the Mining, Geological, and Metallurgical Institute of India to KENNETH C. CASTER, professor of geology, University of Cinicinnati, for his paleontological work in Brazil. The presentation was made by W. D. JOHNSTON, JR., Chief of the Foreign Geology Branch, U. S. Geological Survey.

Mackay & Schnellmann, Geological and Mining Consultants of 115 Moorgate, London, have opened an office in Tehran, Persia, in local charge of D. SIMMONS, assisted by W. YUILL.

W. E. PRATT has addressed several technical audiences recently on the results of the investigation of the petroleum industry he undertook a year ago at the request of the Panel On the Impact of the Peaceful Uses of Atomic Energy. These results were published in January, 1956, by the Government Printing Office, Washington, D. C., as part of the report of the Panel to the Joint Committee on Atomic Energy. In late June he spoke to a joint meeting of the Denver Research Institute and the Atomic Industrial Forum, Inc., at Denver, Colorado, on "The Petroleums—Enduring Sources of Energy." On October 24 he addressed the Eastern Section of the American Association of Petroleum Geologists on "A Long-Range Forecast of Petroleum Supply," in New York City. On November 9 he discussed "Factors Controlling Discovery in the Petroleum Industry," before the Pacific Coast Section of The American Association of Petroleum Geologists at Los Angeles, California.

E. H. ROBIE, after twenty-five years in official capacities with the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), retired as secretary emeritus. A member of AIME since 1919, Mr. Robie became assistant secretary in 1932, secretary in 1949, and secretary emeritus in 1955. Mr. Robie is editor of a supplement to "The Porphyry Coppers," by A. B. Parsons, which will be known as the "The Porphyry Coppers in 1956" and which is expected to be published in 1957. He is editor-in-chief of a new volume on mineral economics which is likely to be published in 1958.

B. E. THOMAS has left consulting work in Albuquerque, N. M., to join the geology department, San Diego State College, Calif.

C. R. JOKISCH, formerly mining engineer, Britannia Corp., Britannia Beach, B. C., Canada, is now at Snow Lake, Manitoba.

A. O. HALL has become exploration engineer for Climax Molybdenum Co., Vancouver, B. C., Canada, having left his position as chief geologist for Northwestern Dept., American Smelting & Refining Co. to do so.

J. D. MORGAN, JR., has opened a consulting office in Washington, D. C. Dr. Morgan's recent assignments have been with the Defense Production Administration in Korea and the Office of Defense Mobilization in Washington, D. C.

THAYER LINDSLEY will devote his time to a newly formed exploration company, having retired as president of Falconbridge Nickel Mines, which he founded 28 years ago.

PAUL KENTS, formerly senior exploration geologist of Northern Peru Mining Corp., is now resident geologist for New Consolidated Canadian Exploration Ltd., Que.

A. E. Moss, chief engineer-geologist of the Iron Ore Co. of Canada, has left the Montreal office for the company's office in Schefferville, Que.

KANJI SHIOBARA, geologist, has been transferred to their Kamioka Mine, Gifuken, Japan, from the Tokyo office of Mitsui Mining & Smelting Co., Ltd.

C. T. SISON, previously geologist with Elizalde & Co., Inc., Manila, P. I., has formed the Republic Resources & Development Corp., of which he is general manager, in Manila.

G. S. HUME has resigned from the Canadian Department of Mines and Technical Surveys to join Westcoast Transmission Co. Ltd., Calgary, Alberta, as geologist.

W. R. BARTON, JR., U. S. Geological Survey, is now at the Agricultural Research Center, Beltsville, Maryland.

G. R. JENKINS, assistant professor of geology at Lehigh University since 1948, succeeds Preston Parr, Jr., as assistant director of the Lehigh University Institute of Research. Mr. Parr has been named associate dean of students at Lehigh.

HIDENOSUKE SANO died some months ago in Tokyo, Japan, at the age of 67. A native of Osaka, Mr. Sano had been associated with Tokyo Imperial University since 1910. He completed his studies there in 1913, and then went on to the Technische Hochschule zu Aachen, Germany, where he remained for two years. After two additional years of study at the University of Birmingham, England, Mr. Sano accepted a position as professor of mining at Meiji College of Technology, Tobata, Japan, in 1918. In 1923 he undertook a similar position at Tokyo Imperial University where he remained until his retirement. He was named Professor Emeritus there in 1949.

H. K. STEPHENSON died in September, 1956. At the time of his death he was program director, earth sciences, of the National Science Foundation, Washington, D. C. Dr. Stephenson was born in Youngstown, Ohio, in 1913, studied at Mt. Union College, and received his doctorate from Princeton University in 1941. He had worked at one time as field assistant for the Newfoundland Geological Survey and was later a geophysicist for the USGS in Wyoming, California, and Pennsylvania.

EVERETTE L. DEGOLYER died at his home in Dallas, Texas, on Dec. 14, at the age of 70 years. He had been in ill health for 6 years. He started Amerada Petroleum Corp. and the Geophysical Research Corp. and helped organize Geophysical Service, Inc. He owned the Saturday Review of Literature and was chairman of the board. He was a former associate editor of this JOURNAL.

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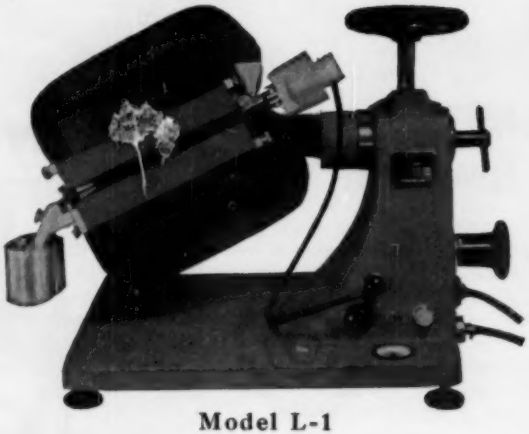

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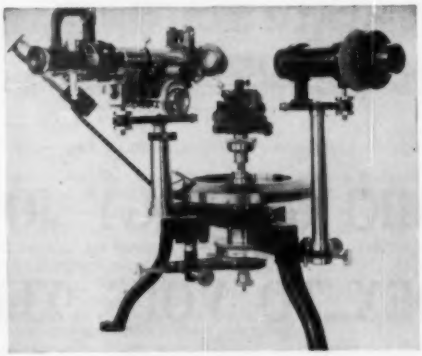

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